FEASIBILITY OF CREATING A NEUTRON DETECTOR ARRAY

FOR THE DETECTION OF SPECIAL NUCLEAR MATERIALS

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FEASIBILITY OF CREATING A NEUTRON DETECTOR ARRAY FOR THE DETECTION OF SPECIAL NUCLEAR MATERIALS

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To Poppa, James Graham, who always wanted a Yellow Jacket in the family

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LIST OF SYMBOLS AND ABBREVIATIONS

CBRN	Chemical, Biological, Radiological, and Nuclear
DoD	Department of Defense
HUMINT	Human Intelligence
IMINT	Imagery Intelligence
JFC	Joint Force Commander
JP	Joint Publication
MCNP	Monte Carlo Neutral Particle
MeV	Mega Electron Volts
RPP	Rectangular Parallelepipeds
SIGINT	Signal Intelligence
SNM	Special Nuclear Material
USG	United States Government
WMD	Weapons of Mass Destruction

SUMMARY

The purpose of this research is to determine the feasibility of creating an energy-dependent neutron detector array that could be used to detect special nuclear materials. The proposed detector array is composed of idealized thermal neutron detectors covered by moderators of differing size, namely thickness and shape. Through a series of Monte Carlo radiation transport calculations, the size, shape, and location of the moderators and detectors were configured to determine the efficacy of obtaining a neutron energy spectrum or spectral information in a single measurement. This approach expands on the concepts of the Bonner Sphere Spectrometer (BSS) which relies on multiple measurements using differing size moderating spheres. Although a proven approach, the traditional BSS method is not practicable for military applications. The alternative approach to the spectrum measurement is the use of detector sums or ratios to distinguish fission neutron spectra from other neutron spectra that might be encountered. Several 5x5 detector/moderator arrays were modeled in MCNP to determine which models would have the best responses to monoenergetic neutron sources. Five models of 5x5 detector arrays were chosen that best optimize the detectors reaction rates over certain energy ranges. This 5x25 detector array was then simulated with monoenergetic neutron sources and fission sources. A least squares fitting method was attempted to find coefficients that would generate a weighted sum of detectors that yield a flat fluence response. The response function did not have a flat response. The 5x25 detector system did produce characteristic curves for moderated and unmoderated fission sources. A 5x30 detector array that contained a 5x5 detector array that had a beryllium layer was also simulated.

The 5x30 detector array had a higher response to high energy neutrons, but not a significant increase for low energy neutrons. The resulting 5x25 system that was designed is capable of being vehicle mounted so it would be mobile. This research shows that it is feasible to create a neutron detector array that is sensitive to neutron energy spectra.

CHAPTER 1

INTRODUCTION

1.1 Background

As outlined in the National Security Strategy, preventing the proliferation of nuclear material and weapons is a high priority for the U.S. Government.[1] Nuclear weapons and materials fall in the broad category of Weapons of Mass Destruction. According to DoD directive 2060.02, it is the DoD's responsibility to counter and deny the proliferation of WMDs.[2] This policy is developed further in the Department of Defense Strategy for Countering Weapons of Mass Destruction. One of the endstates of this policy is that no new actors of concern obtain WMDs.[3] Actors of concern are defined as "state or non-state actors that carry out activities that, left unaddressed, pose a clear potential threat to the strategic objectives of the U.S. Government."[3] In this context an actor of concern "poses a threat of developing, acquiring, proliferating, or employing WMDs."[3]

Countering WMD falls into the DoD strategy outlined in JP 3-26 Counterterrorism and is covered in more detail in JP 3-40 Countering Weapons of Mass Destruction. [4] The Counterterrorism Targeting Cycle is shown in Figure 1. This cycle is used to plan a target that a JFC would decide should be actioned. For example the target could be a criminal organization that transports SNM. The ways and means to counter WMD is shown in Figure 2. Intelligence assets are strongly used to determine the presence and location of WMD.[5]

This information is then used to plan a tactical intervention. There is shortage of CBRN-specific units that have the necessary expertise to accomplish this mission.[5] Also, these teams do not have the tactical expertise to operate in a covert or hostile environment like conventional or special operations forces.[6] This limits their application in certain situations. The generic activities that comprise the key decision points by an actor to acquire, develop, proliferate, or use WMD are illustrated in Figure 3.[5] The goal of the USG is always to stop the continuum before the deployment of WMD. To achieve this goal there either has to be more military personnel capable of providing nuclear expertise to conventional and special operation forces that have additional tactical training, or there has to be a development of specialized equipment that allows conventional and special operations forces to perform the specialized tasks without the necessary expertise.

An important development in combating nuclear WMD would be the creation of a detector that could obtaining a neutron energy spectrum measurement or sufficient spectral information to distinguish between neutron sources in a single measurement. The detector would also have to be able to be operated by the average Soldier. Conventional intelligence gathering processes (HUMINT, IMINT, and SIGINT) have the ability of narrowing down the location of SNM to certain area, but possibly not a single structure or location. A detector coupled with current intelligence resources could allow DoD forces to determine the exact location of SNM with a relatively high certainty.

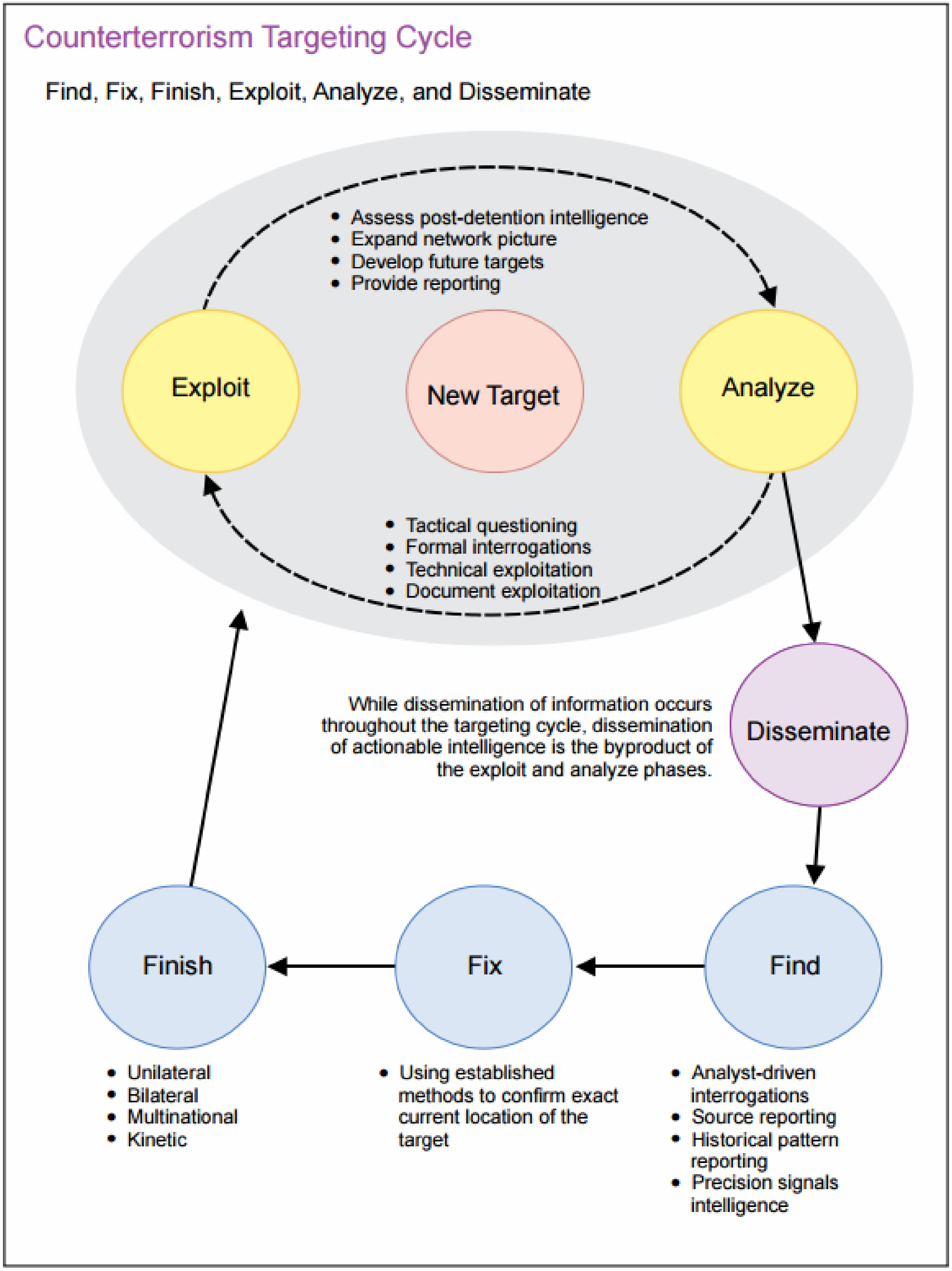

Figure 1. Counterterrorism targeting cycle[4]

Application of the Countering Weapons of Mass Destruction Activity Construct

Countering Weapons of Mass Destruction Lines of Effort	Notional Tasks Performed in Typical Operations and Missions	Countering Weapons of Mass Destruction Activity Categories			
		Understand the Environment	Cooperate with and Support Partners	Control, Defeat, Disable or Dispose of Weapons of Mass Destruction Threats	Safeguard the Force and Manage Consequences
Prevent Acquisition		Locate, Identify, Characterize, Assess, Predict *Intelligence, surveillance, and reconnaissance; medical planning and logistics*	Partner, Coordinate *Security cooperation; unified action; communication synchronization; interdiction; target planning; civil-military cooperation; border security*	Divert and Intercept, Seize, Delay or Disrupt, Neutralize, and Destroy *Targeting; interdiction; information operations; ntelligence, surveillance, and reconnaissance; communication synchronization*	Mitigate and Sustain *Force protection*
Contain, Reduce Threats		Locate, Identify, Characterize, Assess, Predict *Intelligence, surveillance, and reconnaissance; weapons technical intelligence; medical planning and logistics; meteorological and oceanographic operations*	Partner, Coordinate *Security cooperation; unified action; bio-surveillance; strategic communications; targeting; information operations*	Divert and Intercept, Isolate, Secure, Seize, Delay or Disrupt, Neutralize, Destroy, Exploit, Degrade, Reduce, Dismantle, Redirect, and Monitor *Targeting; interdiction; site security; site exploitation; special forces and unified action; cooperative threat reduction; cooperation; civil-military cooperation; sanctions enforcement*	Mitigate, Sustain, Support *Force protection; health services; route reconnaissance*
Respond to Crises		Locate, Identify, Characterize, Assess, Attribute, and Predict *Intelligence, surveillance, and reconnaissance; force posturing; bio-surveillance; forensics and evidence collection; hazard modeling*	Partner, Coordinate *Security cooperation; unified action; civil-military cooperation; communication synchronization; force protection; logistics*	Divert and Intercept, Isolate, Secure, Seize, Delay or Disrupt, Neutralize, Destroy, Exploit, Degrade, Mitigate, Sustain, Support *Targeting; interdiction; site security; information operations; special forces and unified action; force protection*	Mitigate, Sustain, Support *Force protection; health services; decontamination operations; contamination avoidance*

Legend

italic font: typical operations and missions   normal font: tasks

Figure 2. Application of the countering of weapons of mass destruction[5]

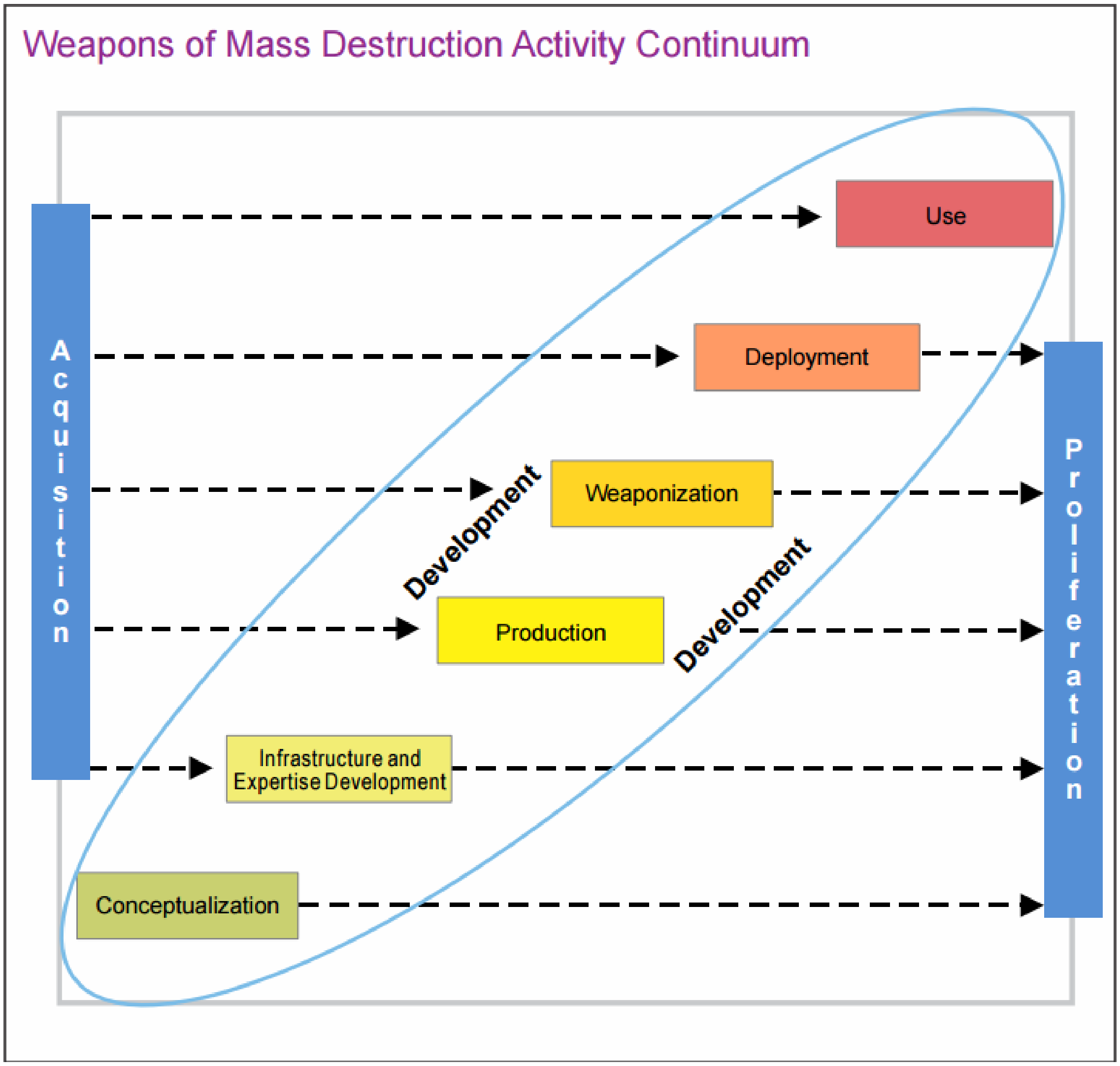

Figure 3. Weapons of mass destruction activity continuum[5]

1.2 Purpose

The purpose of this research is to determine the feasibility of creating an energy-dependent neutron detector array that could be used to detect special nuclear materials. The proposed detector array is composed of idealized thermal neutron detectors covered by moderators of differing size, namely thickness and shape. Through a series of Monte Carlo radiation transport calculations, the size, shape, and location of the moderators and detectors will be investigated to determine the efficacy of obtaining a neutron energy spectrum measurement in a single counting event, i.e. a single measurement. This approach expands on the concept of the

Bonner Sphere Spectrometer (BSS) which relies on multiple measurements using differing size moderating spheres. Although a proven approach, the traditional BSS method is not practical for military use. An alternative approach to the spectrum measurement is the use of detector sums or ratios to distinguish fission neutron spectra from other neutron spectra that might be encountered. The resulting detector system should be capable of being vehicle mounted so it would be mobile.

1.3 Technical Background

1.3.1 Neutron Properties and Interactions

Neutrons are particles that have no electrical charge. This means that they do not directly produce ionization events. Neutrons produced from SNM can have energies ranging from less than 1 eV to about 20 MeV, depending on the surroundings. In order to detect a neutron, the neutron of interest must impart some of its energy through elastic collisions or absorption with other atoms to cause the production of charged particles.[7] By detecting the charged particles created by such reactions, the presence of neutrons can be detected.

1.3.2 Thermal Neutron Detectors

Detectors exist which strongly detect thermal neutrons, which have energies of 0.5 eV or less.[7] The choice of the material used in these detectors are based on several principles. The material must have a high cross section for the reaction of interest so the detector can be small yet still be efficient.[7] The material also must be readily available for use in the detector.[7] Last the energy produced by the reaction has to be high to be able to discriminate against reactions caused by gamma particles or have some other property to distinguish between heavy charged particles and electrons.[7] The models used in this work will use lithium fluoride radiators attached to an alpha detector. The thermal neutron reaction of interest for these detectors is shown below in equation 1.

$$^{6}_{3}Li + ^{1}_{0}n \rightarrow ^{3}_{1}H + ^{4}_{2}\alpha \qquad (1)$$

1.3.3 Bonner Spheres

The probability that neutrons will react with Li-6 decreases as the neutron energy increases.[7] Li-6 has an average absorption thermal neutron microscopic cross section of 838 barns. By surrounding the thermal neutron detector with a moderator, an epithermal or fast neutron can lose kinetic energy through collisions in the moderator so that by the time it reaches the detector it is a low energy neutron. As the size of the moderator increases, the sensitivity of the detector will increase to a point. As the moderator becomes larger there is more of a probability that the neutron will be absorbed or scatter out of the moderator before reaching the detector. When the neutron source is monoenergetic, then there will be an exact moderator thickness that will be the most efficient in producing the best response in the thermal neutron detector.[7] Bramblett, Ewing, and Bonner conducted research to develop such a neutron spectrometer in 1960. They placed LiI(En) scintillators in the center of polyethylene spheres of different diameters. By using the count rate of each sphere in an unfolding process the energy distribution of the incident neutrons can be determined. This is a simple method that only requires the recording of count rates. The disadvantage of this method is that the measurements need to be conducted over a long period of time due to the size of the scintillator.

1.3.4 Size Constraints

The proposed detector design would have to be mobile for it to be useful. That means that it would have to be able to be loaded in a vehicle and transported easily. Also, if used for covert operations, the device would have to be able to fit in box that could be disguised. Three sizes were used as constraints using a GMC Sierra with a standard box, a GMC Canyon with a short box, and a U-Haul moving truck. The table below gives the dimensions for the cargo areas of those vehicles.

Table 1. Width and Lengths of Cargo Areas[8,9,10]

	Width (cm)	Length (cm)
GMC Sierra	129.54	200.41
GMC Canyon	111.76	156.72
U-Haul 15ft Moving Truck	220.98	363.22

CHAPTER 2

METHOD AND MATERIALS

2.1 Computational Methods and MCNP Code

The proposed detector will be able to detect neutrons from SNM and other sources. One of the chief aims of this work is to see if fission neutron spectra can be distinguished from other neutron spectra. This will require all physics and radiation transport be considered in the interactions between the different mediums that the neutrons will travel through. This will be accomplished by using a Monte Carlo transport code. One of the most widely used code for solving particle transport problems is MCNP6. MCNP6 is a general-purpose, continuous-energy, generalized-geometry, time-dependent, Monte Carlo radiation-transport code designed to track many particle types over broad ranges of energies.[11] In this work a track length estimator or in MCNP input language a F4 tally is used to calculate the flux in each detector. The input files used will then request a tally multiplier be applied to the F4 tally to determine the reaction rate (i.e. count rate) in each LiF detector. The $^{6}Li(n,t)^{4}He$ reaction data in the ENDF tables will be used as the tally multiplier.

2.2 Neutron Sources and Neutron Detector

2.2.1 Neutron Sources

The responses, count rate per unit flux, will be computed for monoenergetic neutrons. Resulting responses from several patterned arrays of moderator/detector will be investigated to attempt to determine the optimal moderator configurations. The source will be modeled as a planar source emitting a parallel beam of neutrons. As a result it will have the same surface area as the detector face with an equal distribution along the x and y axis. The source will be located one meter away from the detector array. The following source energies will be used in this work: 1E-8 MeV, 2.5E-8 MeV, 5E-8 MeV, 1E-7 MeV, 1E-6 MeV, 1E-5 MeV, 1E-4 MeV, 1E-3 MeV, 1E-2 MeV, 1E-1 MeV, 1 MeV, 2 MeV, 4 MeV, 6 MeV, 8 MeV, 10 MeV, 12 MeV, 14 MeV, 16 MeV, 18 MeV, 20 MeV. This will be discussed in depth in the method section. Simulations will be conducted with the final detector design with different sources to test the detector against a multi-energy source. The sources simulated will both be moderated and unmoderated. The simulated unmoderated sources used in this work are: a plutonium fission source[12], the Watt fission spectrum[11], an AmBe source[13], an AmB source[13] while the simulated moderated sources are a Cf-252 source in a polyethylene sphere with a 12 in diameter[14], a Cf-252 source in a D2O sphere with a 150mm radius[13], and a Cf-252 source in an iron sphere with a 60 cm diameter[15].

2.2.2 The LiF Detector

The lithium fluoride radiator/thermal neutron detector will be modeled as cylinder that has a 1 cm radius and a 1 cm height. Since the reaction rate in the Li-6 is the marker of concern, the specific material used in the construction of such a system does not have to be LiF.

2.2.3 Moderator Sizes

The moderators are composed of polyethylene. The density of polyethylene is 9.3E-01 g/cm^3. The moderator sections will be modeled in MCNP as a Rectangular Parallelepiped (RPP) with a 4 cm x 4 cm cross sectional area. The heights of the RPPs are based on the radius of Bonner spheres and range from 2.545 to 13.34 cm. Detectors with no moderators will also be used in the simulations. All the moderator heights used are given in Table 2.

Table 2. Polyethylene Moderator Heights[16]

Polyethylene Moderator Heights (cm)				
2.545	5.72	8.895	12.07	15.245
3.18	6.355	9.53	12.705	22.865
3.815	6.99	10.165	13.34	
4.45	7.625	10.8	13.975	
5.085	8.26	11.435	14.61	

2.3 The MCNP Modeling

2.3.1 Detector and Moderator Configurations

The detectors will be placed inside of the moderators. The combination of one moderator with one detector will make up one detector unit. These detector units will be placed in 5x5 arrays to generate the different detector array models used.

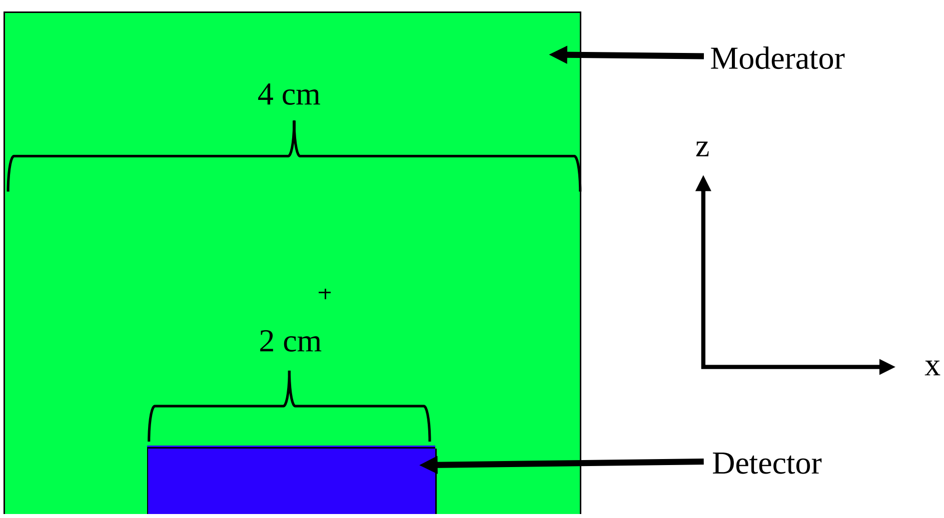

Figure 4. Detector unit

2.3.2 Multi-energy Detector Array Design Method

What is sought is a detector array which has some characteristics to at a minimum distinguish the spectral hardness of the incident neutrons from soft or moderated spectra. The total set of the response curves from this system are used to generate a response matrix. To determine what grouping of moderators should be used for such an array, panels of 5x5 detectors/moderators combinations were first looked at. Based on the 4 cm x 4cm detector unit previously described, such an array would measure 20 cm by 20 cm and easily fitted into the space constraints being considered. A grouping of five of these 25 detector panels would fit within the constraints of our cargo area sizes. Four detector panel models were created to search for a good set of moderators and named wedge, concave, pyramid, and opposite wedge. These layouts are visually shown in figures 5 through 8.

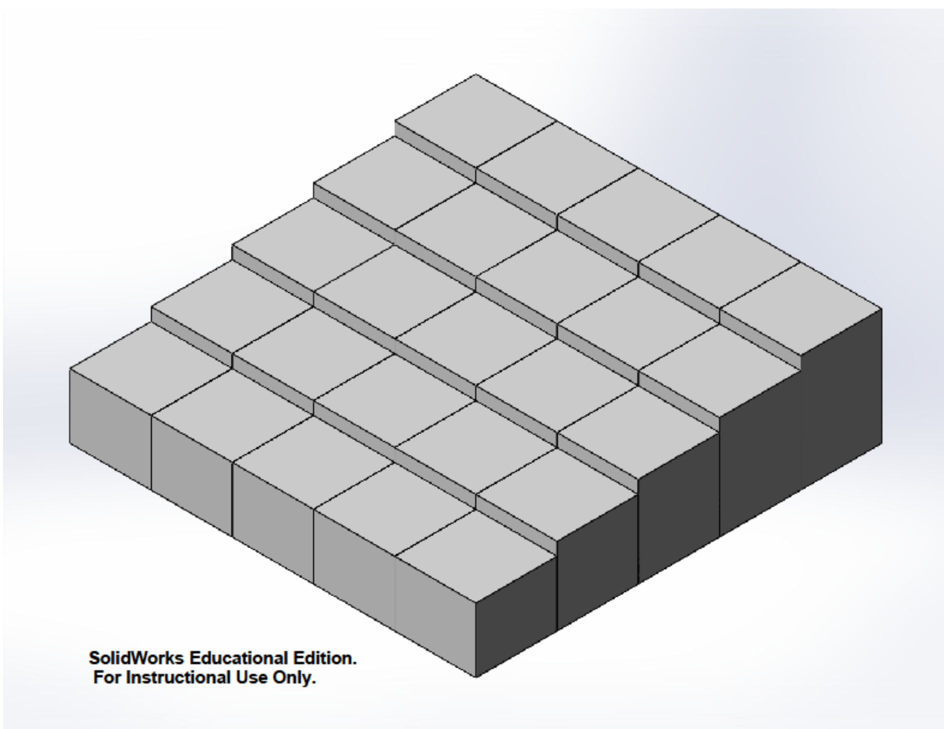

Figure 5. 5x5 detector wedge panel model

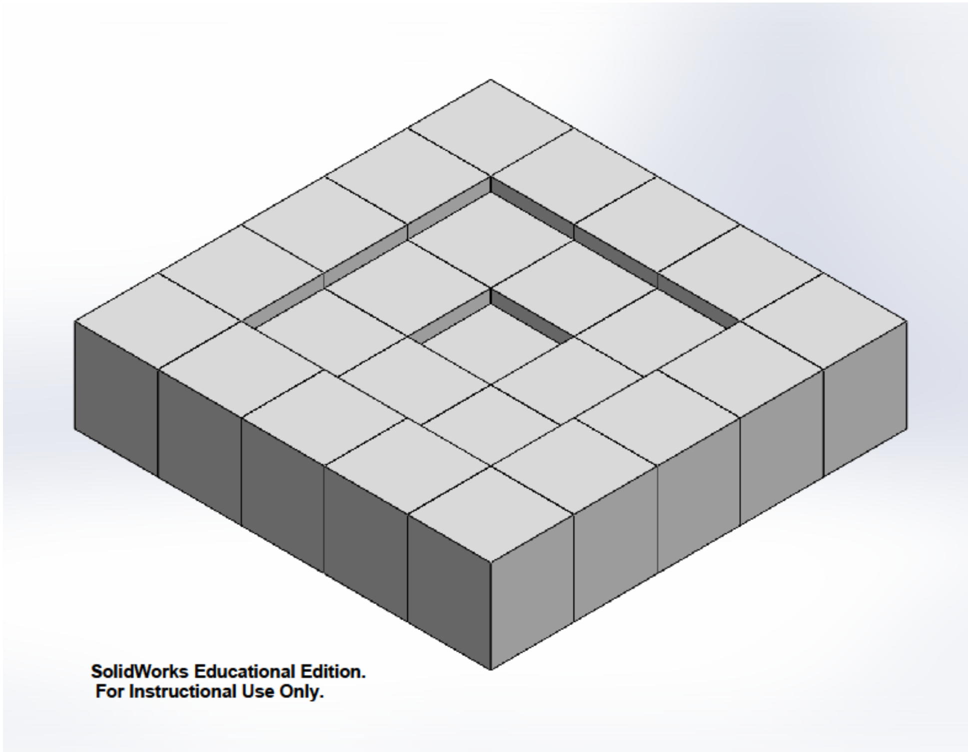

Figure 6. 5x5 detector concave panel model

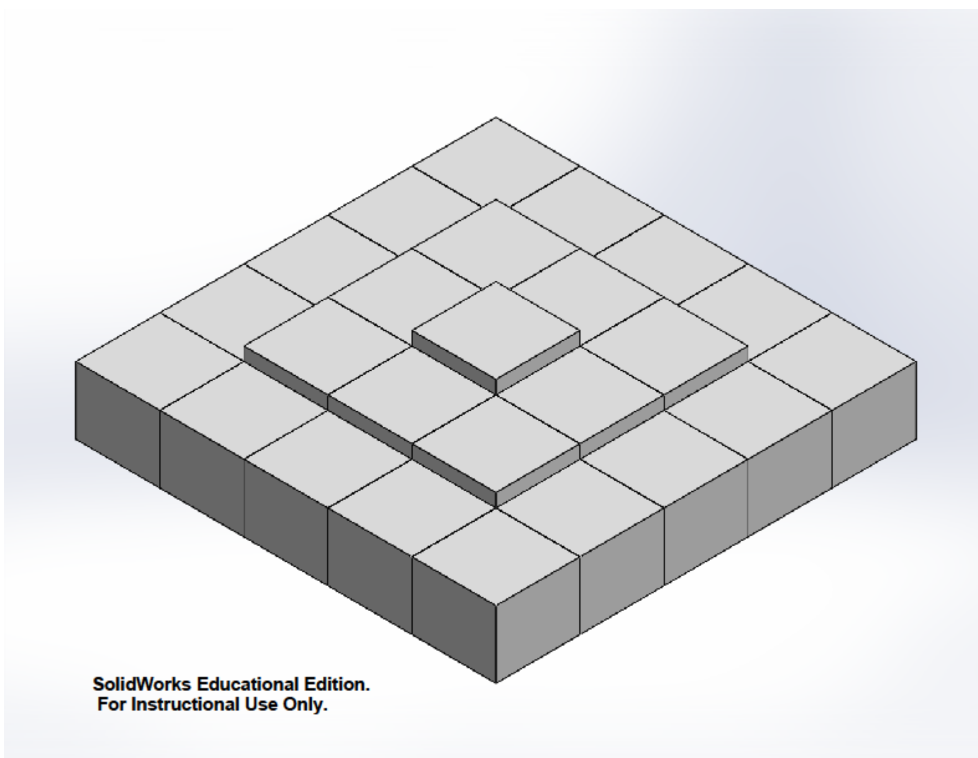

Figure 7. 5x5 detector pyramid panel model

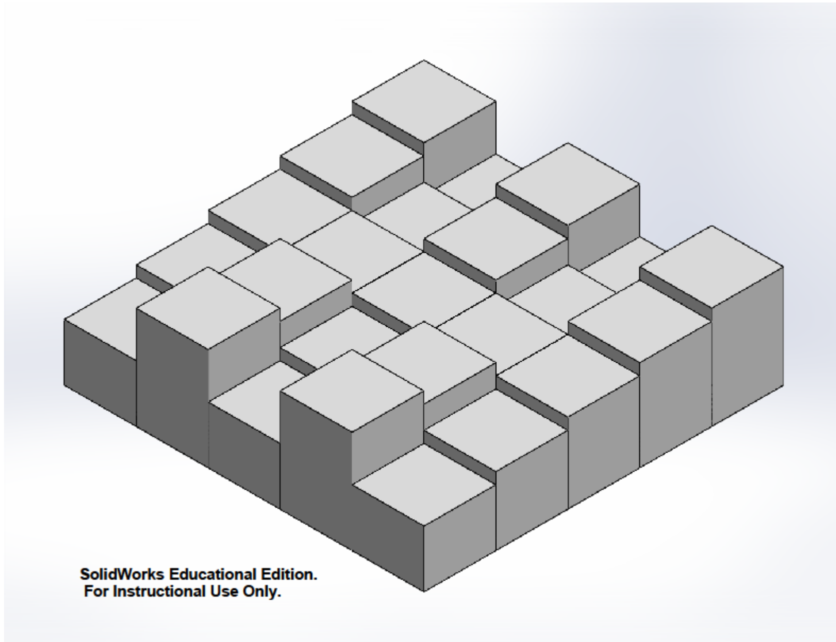

Figure 8. 5x5 detector opposite wedge panel model

For each panel type, multiple models were developed based using the different moderator sizes. Regular combinations of moderators were used in a given panel rather than randomly selected thicknesses so the impacts can be better assessed. Each detector unit was defined as a universe in the MCNP code. Table 3 defines what universe each moderator unit was assigned to (input files are given in Appendix F).

Table 3. Detector Unit MCNP Code Universe Assignments

DETECTOR UNIT MCNP CODE UNIVERSE ASSIGNMENTS
Universe 2- 2.545 cm moderator
Universe 3- 3.18 cm moderator
Universe 4- 3.815 cm moderator
Universe 5- 4.45 cm moderator
Universe 6- 5.085 cm moderator
Universe 7- 5.72 cm moderator
Universe 8- 6.355 cm moderator
Universe 9- 6.99 cm moderator
Universe 10- 7.625 cm moderator
Universe 11- 8.26 cm moderator
Universe 12- 8.895 cm moderator
Universe 13- 9.53 cm moderator
Universe 14- 10.165 cm moderator

Universe 15- 10.8 cm moderator
Universe 16- 11.435 cm moderator
Universe 17- 12.07 cm moderator
Universe 18- 12.705 cm moderator
Universe 19- 13.34 cm moderator
Universe 20- 13.975 cm moderator
Universe 21- 14.61 cm moderator
Universe 22- 15.245 cm moderator
Universe 23- 22.865 cm moderator
Universe 24- no moderator

A naming convention for the panel model used the first letter of the model name and the number of the smallest moderator thickness (universe) used or the moderator thickness (universe) that is on the perimeter of the detector array. Examples are given below for each model type. The number in each cell corresponds to the detector unit (universe) used in that location.

24	2	3	4	5
24	2	3	4	5
24	2	3	4	5
24	2	3	4	5
24	2	3	4	5

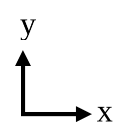

Figure 9. 5x5 detector panel model w24 (wedge)

7	7	7	7	7
7	6	6	6	7
7	6	5	6	7
7	6	6	6	7
7	7	7	7	7

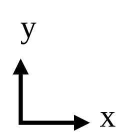

Figure 10. 5x5 detector panel model c7 (concave)

20	20	20	20	20
20	21	21	21	20
20	21	22	21	20
20	21	21	21	20
20	20	20	20	20

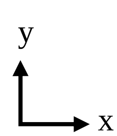

Figure 11. 5x5 detector panel model p20 (pyramid)

10	11	12	13	14
14	13	12	11	10
10	11	12	13	14
14	13	12	11	10
10	11	12	13	14

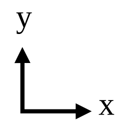

Figure 12. 5x5 detector panel model o10 (opposite wedge)

A total of 21 models were tested for the pyramid and concave models. A total of 19 models were tested for the wedge and reverse wedge models. The detector array is placed in is a rectangular box that is 200 cm x 200 cm x 1056 cm (x axis, y axis, z axis). The system with the detector and planar source is shown below in figure 13.

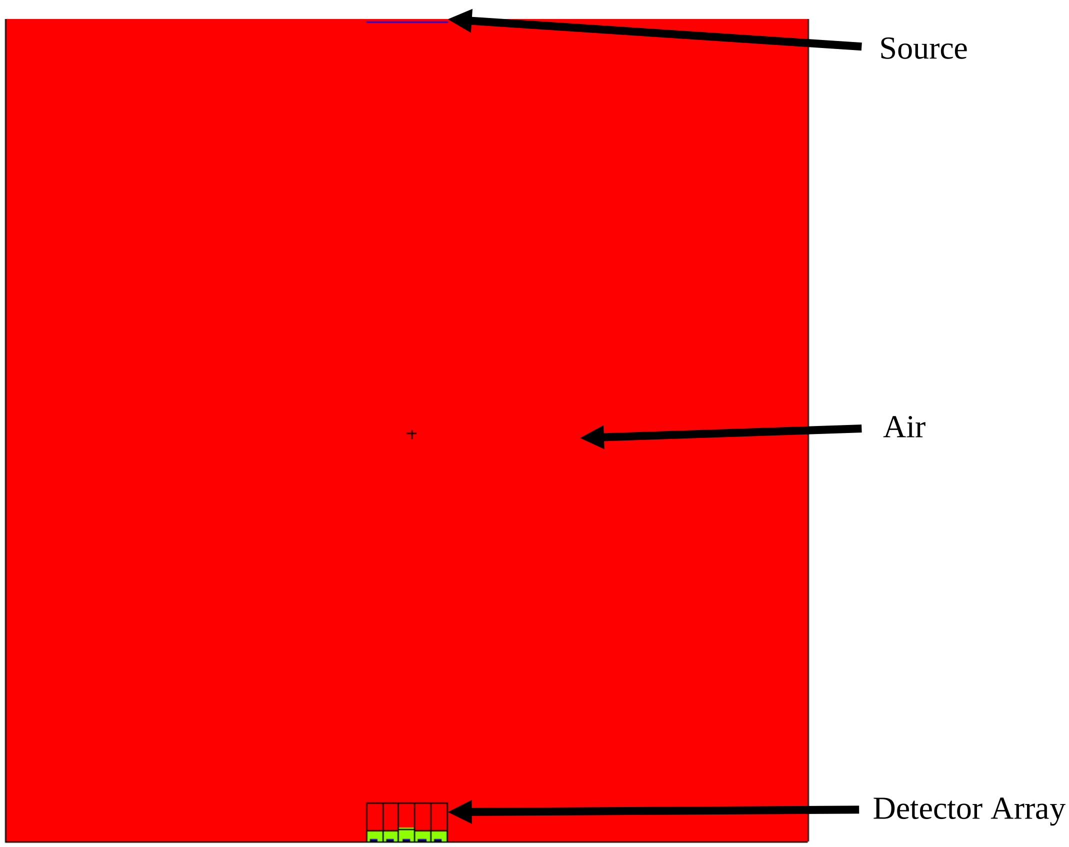

Figure 13. Simulation system with a 5x5 detector panel model p20

This same system is used for all 5x5, 5x25, and 5x30 detector array models. The pyramid model was simulated with all the monoenergetic source energies that were previously listed to see if the general trend followed previous research on Bonner sphere response curves.[17] If the pyramid model follows these trends, then 1E-8 MeV, 1E-4 MeV, 1 MeV, 2 MeV, 4 MeV, 8 MeV, 10 MeV, 14 MeV, 16 MeV, 18 MeV, 20 MeV source energies will be used for the simulation of the remaining 5x5 detector arrays. The total number of (n,t) reactions per neutron in each model will be used to determine the best moderator configurations for the different source energy levels. Based on the results five models will be chosen that best cover five different energy ranges. The five different energy ranges will be chosen based on the data collected. The resulting 5x25 detector array will be simulated with the following source energies: 1E-8 MeV, 1E-7 MeV, 1E-6 MeV, 1E-5 MeV, 1E-4 MeV, 1E-3 MeV, 1E-2 MeV, 1E-1 MeV, 1 MeV, 2 MeV, 3 MeV, 4 MeV, 5 MeV, 6 MeV, 7 MeV, 8 MeV, 9 MeV, 10 MeV, 11 MeV, 12 MeV, 13 MeV, 14 MeV, 15 MeV, 16 MeV, 17 MeV, 18 MeV, 19 MeV, and 20 MeV. The resulting 5x25 detector array model will also be modified by moving all the detectors 15.24 cm away from the moderators. The purpose of this will be how this affects the number of reactions from neutrons traveling from different detector arrays. The resulting 5x25 detector array model will also be modified by placing a 2.54 cm layer of polyethylene behind the detector array. The purpose of this will be how this affects the number of reactions from neutrons scattering back into the detector arrays. Two additional models of 5x30 detector arrays were also simulated. The two models used the chosen 5 models, but contained an additional 5x5 detector array. One model has a sixth detector array that consisted of detector units that all have 7.625 cm moderators with a 2.54 cm beryllium layer. The other model had a sixth detector array that consisted of detector units that will all have 12.705 cm moderators with a 2.54 cm beryllium layer. The purpose of these models were to increase the number of neutrons detected at high energies since beryllium is a neutron multiplier for high energy neutrons. The reaction is shown below in equation 2.

$$^{9}_{4}\mathbf{Be} + \mathbf{n} \rightarrow \mathbf{2}(^{4}_{2}\mathbf{He}) + \mathbf{2n} \tag{2}$$

This was done because previous research shows a drop in the response curve for Bonner spheres for high energy neutrons and that phenomenon should occur for these systems as well.[17] This is shown in the figure below.

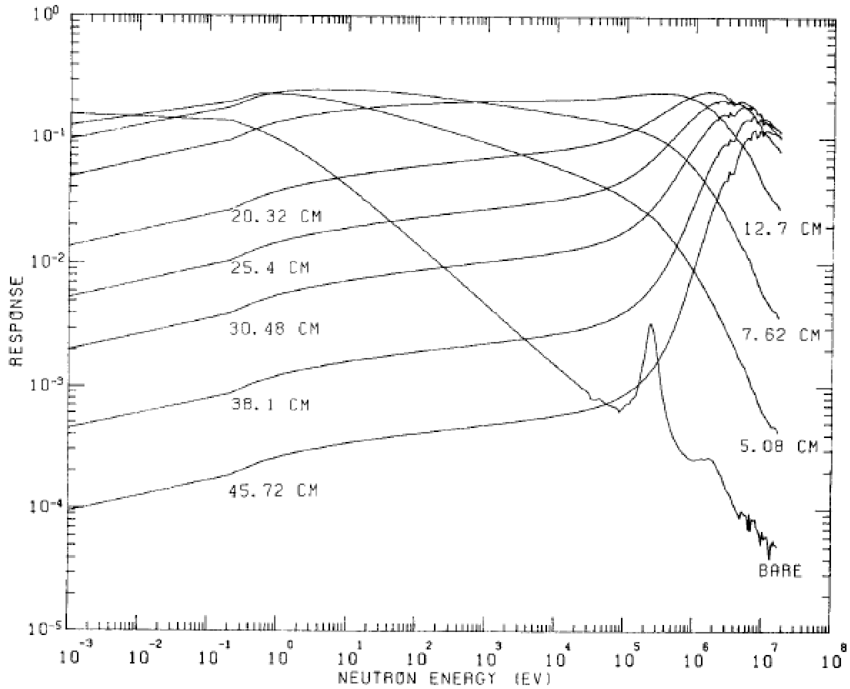

Figure 14. The calculated 171-neutron group responses for the 4 mm LiI detector and the detector inside 5.08, 7.62, 12.7, 20.32, 25.4, 30.48, 38, and 45.72 cm diameter polyethylene spheres[17]

2.3.3 Total Fluence Monitor

The final detector array design should be able to differentiate neutrons in different energy ranges either using a ratio of detector counts or some other characteristic responses such as count distributions from individual panels or detectors or a weighted sum of detectors that give a uniform detection sensitivity for all energy neutrons or for neutrons over limited energy ranges.

It has been shown in previous research that Bonner spheres of different diameters will give different sensitivities as functions of neutron energy.[16] Bonner spheres of certain sizes will have a higher response to specific neutron energies due to the moderation of the neutrons to thermal energies.[16] If the response functions of multiple Bonner spheres were combined with proper weights, then it would be possible to mathematically obtain a single response for all the detectors that resulted in the total fluence. The following equations mathematically represent how this could be done using the least squares fit method. The count rate in a thermal neutron detector embedded in or behind a moderating layer of a given thickness can be written as

$$C_j = \int_0^{E_{\max}} \varepsilon_j(E)\phi(E)\,dE$$

Or for the fluence at a single energy

$$C_j(E_i) = \phi(E_i)\varepsilon_j(E_i)$$

Where $\varepsilon_j(E_i)$ = response of the detector below j^{th} moderator thickness to a unit fluence of neutrons at energy E_i, in counts-cm^2. Of interest in the present case is the feasibility of determining coefficients so that the flux at a given energy can be reconstituted by a weighted sum of the count rates for all N moderator/detector combinations, namely,

$$\phi(E_i) = \sum_{j=1}^{N} a_j C_j(E_i)$$

This can effectively be thought of as finding the coefficients that produce a unit fluence from a weighted sum of the responses at each energy.

$$1 = \sum_{j=1}^{N} a_j \varepsilon_j(E_i)$$

One way to determine the weighting coefficients is to solve for them in the least-squares sense. In the case of a total flux monitor, i.e. a weighted sum of counts that will result in the total flux integrated over all energies, is to minimize the following least-squares problem:

$$\chi^2 = \int_{E_1}^{E_n} \left[1 - \sum_{j=1}^{N} a_j \varepsilon_j \left(E \right) \right]^2 dE$$

Since the responses have only been calculated at a finite number of incident neutron energies (M), the integral can be performed by using the trapezoidal rule:

$$\chi^2 \approx \sum_{i=1}^{M-1} \left\{ \frac{\left[1 - \sum_{j=1}^{N} a_j \varepsilon_j \left(E_i \right) \right]^2 + \left[1 - \sum_{j=1}^{N} a_j \varepsilon_j \left(E_{i+1} \right) \right]^2}{2} \left[E_{i+1} - E_i \right] \right\}$$

The coefficients are then determined by taking the derivative of χ^2 with respect to the p^{th} coefficient a_p and setting the derivative to zero to find the minimum.[18] This is done for *p=1, N* resulting in N equations in N unknowns.

$$\frac{\partial \chi^2}{\partial a_p} = 0 = \frac{\partial}{\partial a_p} \left[\sum_{i=1}^{M-1} \left\{ \frac{\left[1 - \sum_{j=1}^{N} a_j \varepsilon_j \left(E_i \right) \right]^2 + \left[1 - \sum_{j=1}^{N} a_j \varepsilon_j \left(E_{i+1} \right) \right]^2}{2} \left[E_{i+1} - E_i \right] \right\} \right]$$

The equations are then rearranged and solved.

$$0=\frac{\partial}{\partial a_p}\left[\sum_{i=1}^{M-1}\left\{\left(\left[1-\sum_{j=1}^{N}a_j\varepsilon_j\left(E_i\right)\right]^2+\left[1-\sum_{j=1}^{N}a_j\varepsilon_j\left(E_{i+1}\right)\right]^2\right)\left[E_{i+1}-E_i\right]\right\}\right]$$

$$0=\sum_{i=1}^{M-1}\left\{\left(2\left[1-\sum_{j=1}^{N}a_j\varepsilon_j\left(E_i\right)\right]\varepsilon_p\left(E_i\right)+2\left[1-\sum_{j=1}^{N}a_j\varepsilon_j\left(E_{i+1}\right)\right]\varepsilon_p\left(E_{i+1}\right)\right)\left[E_{i+1}-E_i\right]\right\}$$

$$0=\sum_{i=1}^{M-1}\left\{\left(\left[1-\sum_{j=1}^{N}a_j\varepsilon_j\left(E_i\right)\right]\varepsilon_p\left(E_i\right)+\left[1-\sum_{j=1}^{N}a_j\varepsilon_j\left(E_{i+1}\right)\right]\varepsilon_p\left(E_{i+1}\right)\right)\left[E_{i+1}-E_i\right]\right\}$$

$$0=\sum_{i=1}^{M-1}\left\{\left(\left[1-\sum_{j=1}^{N}a_j\varepsilon_j\left(E_i\right)\right]\varepsilon_p\left(E_i\right)+\left[1-\sum_{j=1}^{N}a_j\varepsilon_j\left(E_{i+1}\right)\right]\varepsilon_p\left(E_{i+1}\right)\right)\left[E_{i+1}-E_i\right]\right\}$$

$$0=\sum_{i=1}^{M-1}\Big\{\Big(\big[1-a_1\varepsilon_1\left(E_i\right)-a_2\varepsilon_2\left(E_i\right)-a_3\varepsilon_3\left(E_i\right)-\cdots-a_p\varepsilon_p\left(E_i\right)-\cdots-a_N\varepsilon_N\left(E_i\right)\big]\varepsilon_p\left(E_i\right)+$$
$$\big[1-a_1\varepsilon_1\left(E_{i+1}\right)-a_2\varepsilon_2\left(E_{i+1}\right)-a_3\varepsilon_3\left(E_{i+1}\right)-\cdots-a_p\varepsilon_p\left(E_{i+1}\right)-\cdots-a_N\varepsilon_N\left(E_{i+1}\right)\big]\varepsilon_p\left(E_{i+1}\right)\Big)\times\left[E_{i+1}-E_i\right]\Big\}$$

Further simplification leads to

$$0=\sum_{i=1}^{M-1}\Big\{\Big(\big[\varepsilon_p\left(E_i\right)-a_1\varepsilon_1\left(E_i\right)\varepsilon_p\left(E_i\right)-a_2\varepsilon_2\left(E_i\right)\varepsilon_p\left(E_i\right)-a_3\varepsilon_3\left(E_i\right)\varepsilon_p\left(E_i\right)-\cdots-a_p\varepsilon_p^2\left(E_i\right)-\cdots-a_N\varepsilon_N\left(E_i\right)\varepsilon_p\left(E_i\right)\big]+$$
$$\big[\varepsilon_p\left(E_{i+1}\right)-a_1\varepsilon_1\left(E_{i+1}\right)\varepsilon_p\left(E_{i+1}\right)-a_2\varepsilon_2\left(E_{i+1}\right)\varepsilon_p\left(E_{i+1}\right)-a_3\varepsilon_3\left(E_{i+1}\right)\varepsilon_p\left(E_{i+1}\right)-\cdots-a_p\varepsilon_p^2\left(E_{i+1}\right)-\cdots-a_{N\varepsilon_p\left(E_{i+1}\right)}\varepsilon_N\left(E_{i+1}\right)\big]\Big)\times\left[E_{i+1}-E_i\right]\Big\}$$

$$0=\sum_{i=1}^{M-1}\Big\{\left[\varepsilon_p\left(E_i\right)+\varepsilon_p\left(E_{i+1}\right)\right]-a_1\left[\varepsilon_1\left(E_i\right)\varepsilon_p\left(E_i\right)+\varepsilon_1\left(E_{i+1}\right)\varepsilon_p\left(E_{i+1}\right)\right]-a_2\left[\varepsilon_2\left(E_i\right)\varepsilon_p\left(E_i\right)+\varepsilon_2\left(E_{i+1}\right)\varepsilon_p\left(E_{i+1}\right)\right]$$
$$-a_3\left[\varepsilon_3\left(E_i\right)\varepsilon_p\left(E_i\right)+\varepsilon_3\left(E_{i+1}\right)\varepsilon_p\left(E_{i+1}\right)\right]-\cdots-a_p\left[\varepsilon_p^2\left(E_i\right)+\varepsilon_p^2\left(E_{i+1}\right)\right]-\cdots-a_N\left[\varepsilon_N\left(E_i\right)\varepsilon_p\left(E_i\right)+\varepsilon_N\left(E_{i+1}\right)\varepsilon_p\left(E_{i+1}\right)\right]\left[E_{i+1}-E_i\right]\Big\}$$

$$\sum_{i=1}^{M-1}\left\{\left[\varepsilon_p\left(E_i\right)+\varepsilon_p\left(E_{i+1}\right)\right]\left[E_{i+1}-E_i\right]\right\}=a_1\sum_{i=1}^{M-1}\left\{\left[\varepsilon_1\left(E_i\right)\varepsilon_p\left(E_i\right)+\varepsilon_1\left(E_{i+1}\right)\varepsilon_p\left(E_{i+1}\right)\right]\left[E_{i+1}-E_i\right]\right\}$$
$$+a_2\sum_{i=1}^{M-1}\left\{\left[\varepsilon_2\left(E_i\right)\varepsilon_p\left(E_i\right)+\varepsilon_2\left(E_{i+1}\right)\varepsilon_p\left(E_{i+1}\right)\right]\left[E_{i+1}-E_i\right]\right\}+a_3\sum_{i=1}^{M-1}\left\{\left[\varepsilon_3\left(E_i\right)\varepsilon_p\left(E_i\right)+\varepsilon_3\left(E_{i+1}\right)\varepsilon_p\left(E_{i+1}\right)\right]\left[E_{i+1}-E_i\right]\right\}$$
$$+\cdots+a_p\sum_{i=1}^{M-1}\left\{\left[\varepsilon_p^2\left(E_i\right)+\varepsilon_p^2\left(E_{i+1}\right)\right]\left[E_{i+1}-E_i\right]\right\}+\cdots+a_N\sum_{i=1}^{M-1}\left\{\left[\varepsilon_N\left(E_i\right)\varepsilon_p\left(E_i\right)+\varepsilon_N\left(E_{i+1}\right)\varepsilon_p\left(E_{i+1}\right)\right]\left[E_{i+1}-E_i\right]\right\}$$

This set of N equations can be written in matrix form

$$\underline{\underline{M}}\,\vec{a}=\vec{b}$$

Where

$$\vec{\mathbf{a}} = \begin{bmatrix} a_1 \\ a_2 \\ a_3 \\ \vdots \\ \vdots \\ a_{N-1} \\ a_N \end{bmatrix}$$

and

$$\vec{\mathbf{b}} = \begin{bmatrix} \sum_{i=1}^{M-1} \left\{ \left[\varepsilon_1(E_i) + \varepsilon_1(E_{i+1}) \right] \left[E_{i+1} - E_i \right] \right\} \\ \sum_{i=1}^{M-1} \left\{ \left[\varepsilon_2(E_i) + \varepsilon_2(E_{i+1}) \right] \left[E_{i+1} - E_i \right] \right\} \\ \sum_{i=1}^{M-1} \left\{ \left[\varepsilon_3(E_i) + \varepsilon_3(E_{i+1}) \right] \left[E_{i+1} - E_i \right] \right\} \\ \vdots \\ \vdots \\ \sum_{i=1}^{M-1} \left\{ \left[\varepsilon_{N-1}(E_i) + \varepsilon_{N-1}(E_{i+1}) \right] \left[E_{i+1} - E_i \right] \right\} \\ \sum_{i=1}^{M-1} \left\{ \left[\varepsilon_N(E_i) + \varepsilon_N(E_{i+1}) \right] \left[E_{i+1} - E_i \right] \right\} \end{bmatrix}$$

The $\underline{\underline{M}}$ matrix is

$$\begin{bmatrix} \sum_{i=1}^{M-1}\{[\varepsilon_1^2(E_i)+\varepsilon_1^2(E_{i+1})][E_{i+1}-E_i]\} & \sum_{i=1}^{M-1}\{[\varepsilon_2(E_i)\varepsilon_1(E_i)+\varepsilon_2(E_{i+1})\varepsilon_1(E_{i+1})][E_{i+1}-E_i]\} & \sum_{i=1}^{M-1}\{[\varepsilon_3(E_i)\varepsilon_1(E_i)+\varepsilon_3(E_{i+1})\varepsilon_1(E_{i+1})][E_{i+1}-E_i]\} & \cdots & \sum_{i=1}^{M-1}\{[\varepsilon_N(E_i)\varepsilon_1(E_i)+\varepsilon_N(E_{i+1})\varepsilon_1(E_{i+1})][E_{i+1}-E_i]\} \\ \sum_{i=1}^{M-1}\{[\varepsilon_2(E_i)\varepsilon_1(E_i)+\varepsilon_2(E_{i+1})\varepsilon_1(E_{i+1})][E_{i+1}-E_i]\} & \sum_{i=1}^{M-1}\{[\varepsilon_2^2(E_i)+\varepsilon_2^2(E_{i+1})][E_{i+1}-E_i]\} & \sum_{i=1}^{M-1}\{[\varepsilon_3(E_i)\varepsilon_2(E_i)+\varepsilon_3(E_{i+1})\varepsilon_2(E_{i+1})][E_{i+1}-E_i]\} & \cdots & \sum_{i=1}^{M-1}\{[\varepsilon_N(E_i)\varepsilon_2(E_i)+\varepsilon_N(E_{i+1})\varepsilon_2(E_{i+1})][E_{i+1}-E_i]\} \\ \sum_{i=1}^{M-1}\{[\varepsilon_3(E_i)\varepsilon_1(E_i)+\varepsilon_3(E_{i+1})\varepsilon_1(E_{i+1})][E_{i+1}-E_i]\} & \sum_{i=1}^{M-1}\{[\varepsilon_2(E_i)\varepsilon_3(E_i)+\varepsilon_2(E_{i+1})\varepsilon_3(E_{i+1})][E_{i+1}-E_i]\} & \sum_{i=1}^{M-1}\{[\varepsilon_3^2(E_i)+\varepsilon_3^2(E_{i+1})][E_{i+1}-E_i]\} & \cdots & \sum_{i=1}^{M-1}\{[\varepsilon_N(E_i)\varepsilon_3(E_i)+\varepsilon_N(E_{i+1})\varepsilon_3(E_{i+1})][E_{i+1}-E_i]\} \\ \vdots & \vdots & \vdots & \ddots & \vdots \\ \sum_{i=1}^{M-1}\{[\varepsilon_N(E_i)\varepsilon_1(E_i)+\varepsilon_N(E_{i+1})\varepsilon_1(E_{i+1})][E_{i+1}-E_i]\} & \sum_{i=1}^{M-1}\{[\varepsilon_2(E_i)\varepsilon_N(E_i)+\varepsilon_2(E_{i+1})\varepsilon_N(E_{i+1})][E_{i+1}-E_i]\} & \sum_{i=1}^{M-1}\{[\varepsilon_3(E_i)\varepsilon_N(E_i)+\varepsilon_3(E_{i+1})\varepsilon_N(E_{i+1})][E_{i+1}-E_i]\} & \cdots & \sum_{i=1}^{M-1}\{[\varepsilon_N^2(E_i)+\varepsilon_N^2(E_{i+1})][E_{i+1}-E_i]\} \end{bmatrix}$$

Where the elements of M are:

$$\boldsymbol{M_{kk}} = \sum_{\boldsymbol{i=1}}^{\boldsymbol{M-1}} \{[\boldsymbol{\varepsilon_k}^{\boldsymbol{2}}(\boldsymbol{E_i}) + \boldsymbol{\varepsilon_k}^{\boldsymbol{2}}(\boldsymbol{E_{i+1}})][\boldsymbol{E_{i+1}} - \boldsymbol{E_i}]\}$$

$$\boldsymbol{M_{kl}} = \sum_{\boldsymbol{i=1}}^{\boldsymbol{M-1}} \{[\boldsymbol{\varepsilon_l}(\boldsymbol{E_i})\boldsymbol{\varepsilon_k}(\boldsymbol{E_i}) + \boldsymbol{\varepsilon_l}(\boldsymbol{E_{i+1}})\boldsymbol{\varepsilon_k}(\boldsymbol{E_{i+1}})][\boldsymbol{E_{i+1}} - \boldsymbol{E_i}]\}$$

Solving for the coefficient vector leads to the a_j values that will provide the best fit in the least-squares sense for obtaining the total fluence from the count rates.

An option that is of interest in the location of SNM might well be selecting the a_j values so that there is virtually no response due the summation of the counts over a given energy range and a reconstitution of the actual fluence over another energy range. For example, if we only want the total flux in the "fission" energy range, we might use this least-squares formulation as our starting point:

$$\chi^2 = \int_{E_1}^{E_k} \left[0 - \sum_{j=1}^{N} a_j \varepsilon_j \left(E \right) \right]^2 dE + \int_{E_k}^{E_n} \left[1 - \sum_{j=1}^{N} a_j \varepsilon_j \left(E \right) \right]^2 dE$$

$$\chi^2 \approx \sum_{i=1}^{k-1} \left\{ \frac{\left[\sum_{j=1}^{N} a_j \varepsilon_j \left(E_i \right) \right]^2 + \left[\sum_{j=1}^{N} a_j \varepsilon_j \left(E_{i+1} \right) \right]^2}{2} \left[E_{i+1} - E_i \right] \right\} + \sum_{i=k}^{M-1} \left\{ \frac{\left[1 - \sum_{j=1}^{N} a_j \varepsilon_j \left(E_i \right) \right]^2 + \left[1 - \sum_{j=1}^{N} a_j \varepsilon_j \left(E_{i+1} \right) \right]^2}{2} \left[E_{i+1} - E_i \right] \right\}$$

One could similarly do fits over different energy ranges, like low energy, medium energies and compare the weighted sums to give insight to the nature of the neutron spectrum hitting the detectors.

CHAPTER 3

RESULTS

3.1 Optimization of 5x5 Detector Arrays

First, all configurations for the pyramid model were simulated at all energy levels. The results are shown in appendix A. Since all models utilize the same size detector units, the assumption was made that the other detector configurations would follow the same response pattern as the pyramid model. Based on this assumption, configuration models that had larger thickness moderators were not simulated at low source energies, and configuration models that had smaller thickness moderators were not simulated at high source energies. So the concave, wedge, and opposite wedge models were not simulated at all of the same source energies as the pyramid model. These models were simulated at with monoenergetic neutron sources of the following energies: 1E-8 MeV, 1E-4 MeV, 1 MeV, 4 MeV, 8 MeV, 10 MeV, 14 MeV, 16 MeV, 18 MeV, 20 MeV. This was done to reduce the amount of time needed for running simulations.

If there was a significant difference between the models, then more simulations would be performed with additional source energies. The remaining models did not have a significant difference in the response pattern that the pyramid model followed. The final results are compared in appendix A and shown in Figure 16.

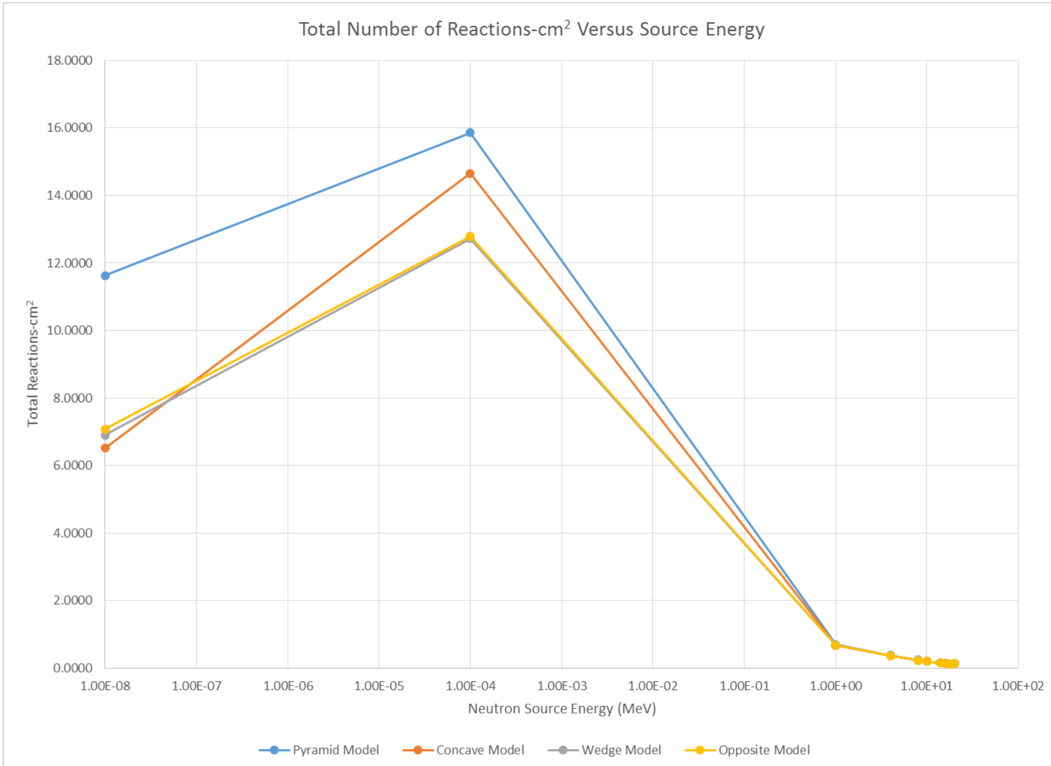

Figure 15. Greatest total number of reaction-cm^2 versus source energy for 5x5 detector arrays

The results show that the pyramid model had the highest number of total reactions for all source energy levels except at 18 and 20 MeV. The pyramid model had the greatest number of models that performed the best with high energy neutron sources. Based on the data it was determined that the pyramid model would be used in the remainder of the study. The pyramid model data were then analyzed to determine the best pyramid model configurations to cover five energy ranges in a 5x25 detector array. For the energy range 1E-8 to 1E-5 MeV, the p24 model was chosen. For the energy range 1E-4 to 1E-1 MeV, the p2 model was chosen. For the energy range 1 to 4 MeV, the p7 model was chosen. For the energy range 6 to 12 MeV, the p13 model was chosen.

For the energy range 14 to 20 MeV, the p15 model was chosen. These detector arrays were placed in series along the x axis in the positive x direction as shown in Figure 16.

24	24	24	24	24	2	2	2	2	2	7	7	7	7	7	13	13	13	13	13	15	15	15	15	15
24	2	2	2	24	2	3	3	3	2	7	8	8	8	7	13	14	14	14	13	15	16	16	16	15
24	2	3	2	24	2	3	4	3	2	7	8	9	8	7	13	14	15	14	13	15	16	17	16	15
24	2	2	2	24	2	3	3	3	2	7	8	8	8	7	13	14	14	14	13	15	16	16	16	15
24	24	24	24	24	2	2	2	2	2	7	7	7	7	7	13	13	13	13	13	15	15	15	15	15

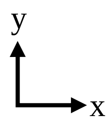

Figure 16. Configuration of the final 5x25 detector array model

3.2 Optimization of 5x25 Detector Array

3.2.1 5x25 Detector Array

The 5x25 detector array was then simulated at the following energies: 1E-8 MeV, 1E-7 MeV, 1E-6 MeV, 1E-5 MeV, 1E-4 MeV, 1E-3 MeV, 1E-2 MeV, 1E-1 MeV, 1 MeV, 2 MeV, 3 MeV, 4 MeV, 5 MeV, 6 MeV, 7 MeV, 8 MeV, 9 MeV, 10 MeV, 11 MeV, 12 MeV, 13 MeV, 14 MeV, 15 MeV, 16 MeV, 17 MeV, 18 MeV, 19 MeV, and 20 MeV. The results are listed in Appendix B.

3.2.2 5x25 Detector Array with Separation Between Detectors and Moderators

The same 5x25 detector array was then simulated at the same neutron source energies with a 15.24 cm space between the moderators and the detectors. The results are in appendix B.

3.2.3 5x25 Detector Array with a 2.54 cm Polyethylene Layer Behind the Detector Array

The same 5x25 detector array was then simulated at the same neutron source energies with a 2.54 cm polyethylene layer behind the moderators and the detectors. The results are in appendix B.

3.2.4 Comparison of the Three 5x25 Detector Arrays

The data shows that the number of reaction-cm^2 in the detectors decreased in the model with the space between the moderators and the detectors, but the number of reactions-cm^2 increased when a polyethylene backing was added. The number of reactions-cm^2 significantly increased for the 20 MeV source. The results are shown Figure 17.

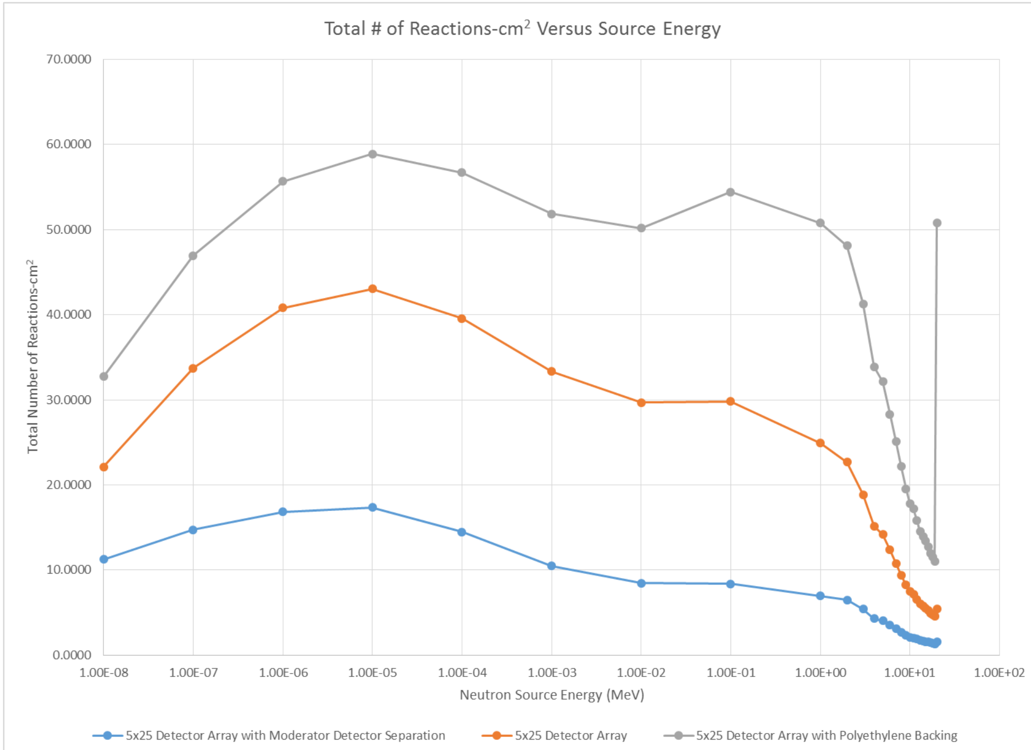

Figure 17. Total number of reactions-cm^2 by source energy for the 5x25 detector arrays

3.3 Addition of a Beryllium Layer in a 5x30 Detector Array

For the 5x30 detector arrays the total number of reactions for neutrons 1E-8 MeV and below were higher than for the 5x25 detector array, but the results are very similar. The 5x30 detector arrays had a significant increase in response for neutron energies above 1 MeV. Figure 17 shows the total number of reactions for the 5x25 and two 5x30 detector arrays. A table with the values and comparison of reactions-cm^2 per neutron for the 5x25 and 5x30 detector arrays is included in appendix C.

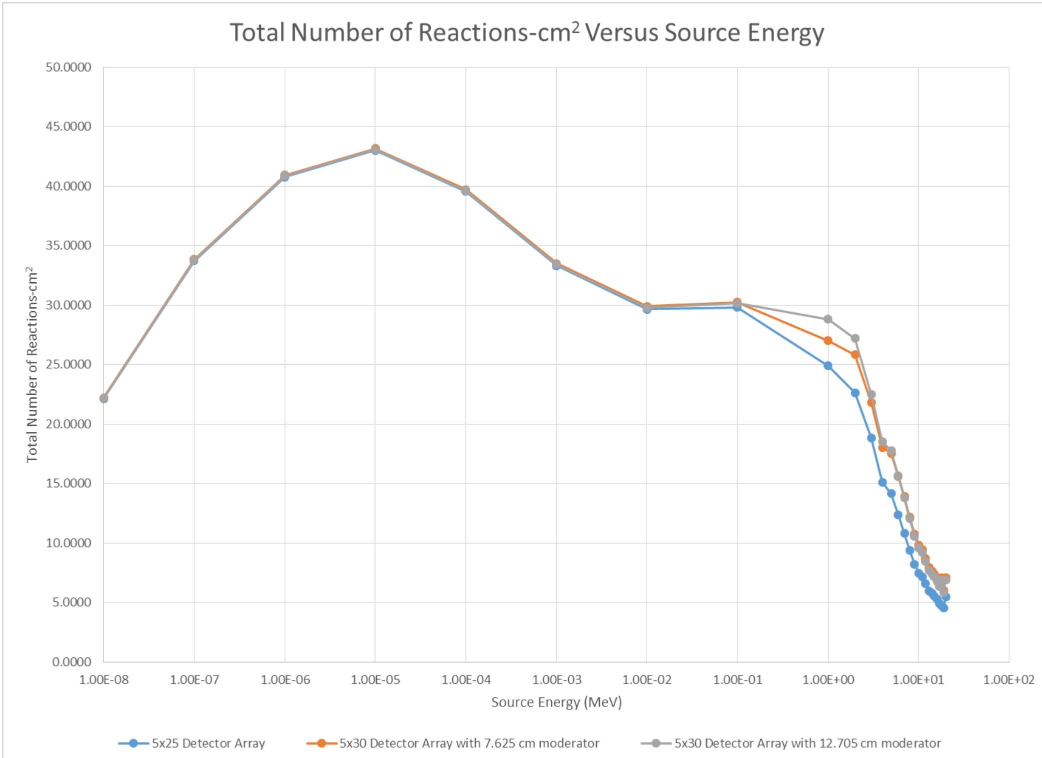

Figure 18. Total number of reactions by source energy for the 5x25 and 5x30 detector arrays

3.4 5x25 Detector Array Model Simulated with Moderated and Unmoderated Sources

The 5x25 detector array modeled with the fission sources described earlier gave similar response curves for unmoderated sources shown in figure 20. The 5x25 detector array had a higher response in the detector arrays that were optimized for lower energy ranges as shown in figure 19. The following sources were used: a plutonium source[12], the Watt fission spectrum[11], an AmBe source[13], an AmB source[13], a Cf-252 source in a polyethylene sphere with a 12 in diameter[14], a Cf-252 source in a D_2O sphere with a 150mm radius[13], and a Cf-252 source in an iron sphere with a 60 cm diameter[15]. The data for figures 19 and 20 is included in appendix D.

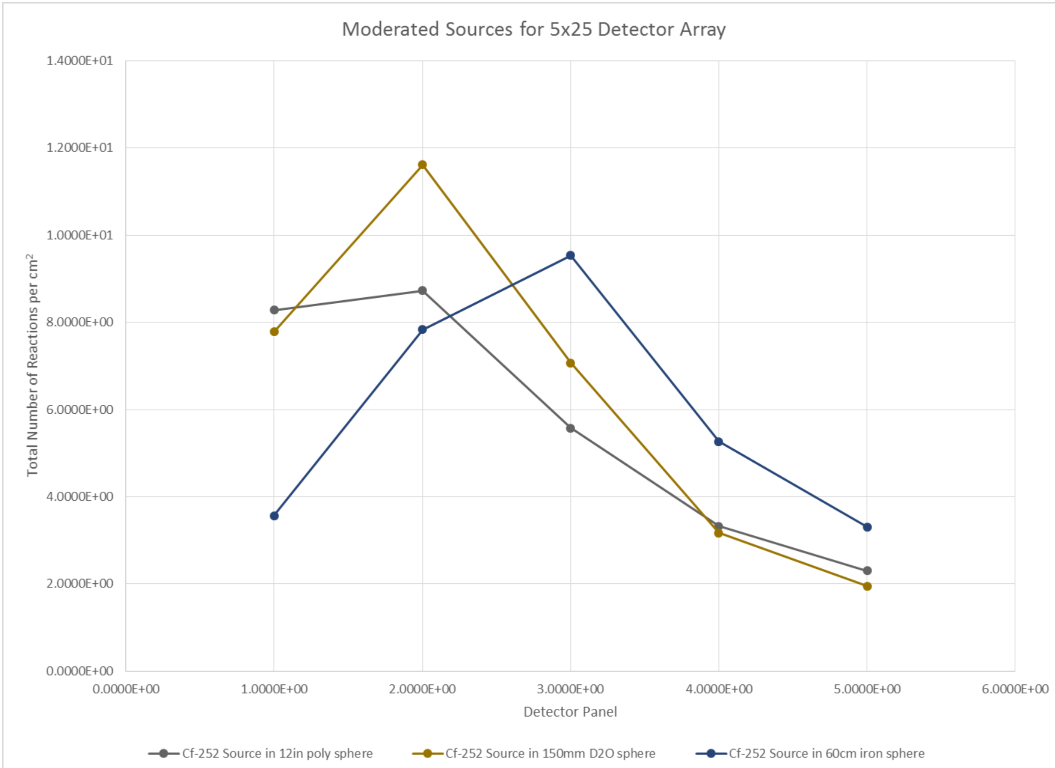

Figure 19. Total number of reactions-cm^2 per detector panel for moderated sources for the 5x25 detector array

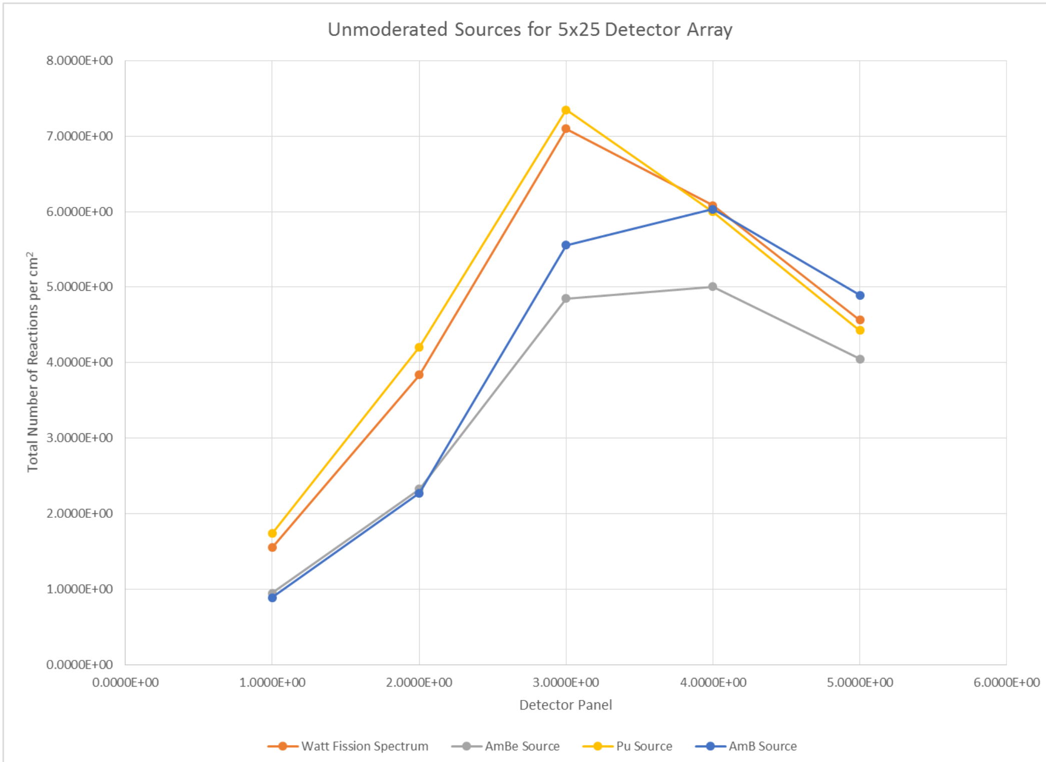

Figure 20. Total number of reactions-cm^2 per detector panel for unmoderated sources for the 5x25 detector array

3.5 LEAST SQUARES FIT FOR 5X25 DETECTOR ARRAY

The data obtained from the 5x25 detector were used with the least-squares fit method to solve for the weights needed to develop a weighted sum calculation of fluence. The total reactions per neutron for each 5x5 detector array panel were used to reduce the dimensionality of the problem. Appendix E contains tables that show the results, data, and matrixes used to compute the coefficients. The resulting weighted sums for the 5x25 detector array $\sum_{j=1}^{n} a_j \varepsilon_j(E)$ for every energy level was not equal to 1, therefore the calculated weights did not give a flat response.

Based on these results more MCNP simulations were done with additional energy levels. The resulting weighted sums for the 5x25 detector array $\sum_{j=1}^{n} a_j \varepsilon_j(E)$ with the additional energy level was not equal to 1 but they were much closer. Appendix E contains tables that show the results, data, and matrixes used to compute the coefficients with the additional energy levels. Figure 21 shows the results.

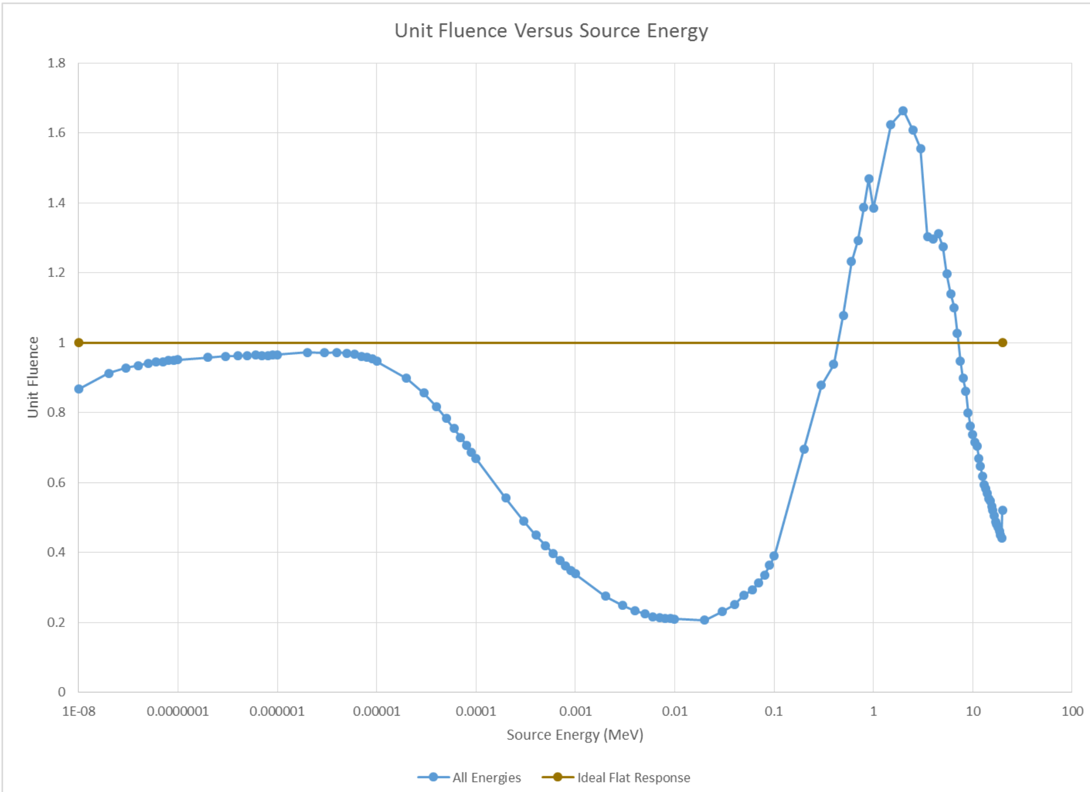

Figure 21. Unit fluence versus source energy for the 5x25 detector array

The least-squares fit method was then applied to the energy ranges chosen for each panel. When the least-squares fit method was applied to only to the specific energy ranges the resulting weighted sums for the 5x25 detector array were very close to one for each specific energy in the ranges. This is shown below in Figures 22 and 23.

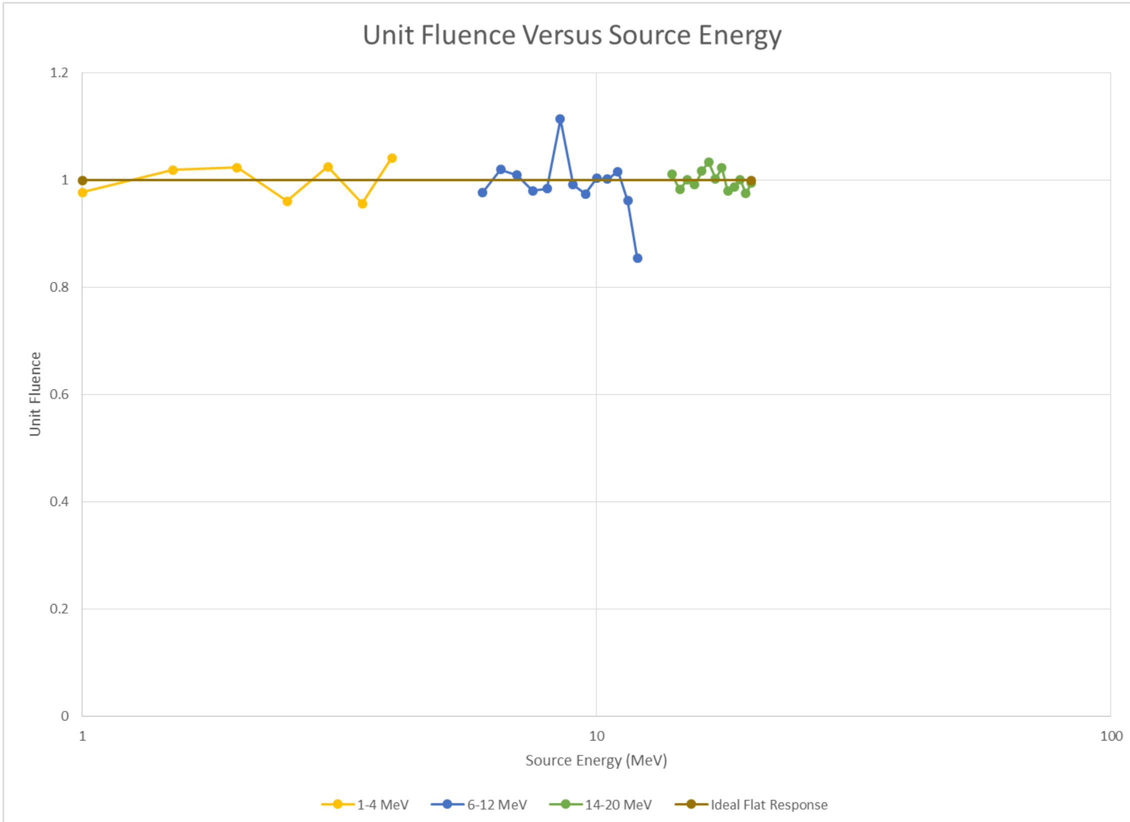

Figure 22. Unit fluence versus source energy for the 5x25 detector array applied to the following energy ranges: 1 to 4 MeV, 6 to 12 MeV, and 14 to 20 MeV

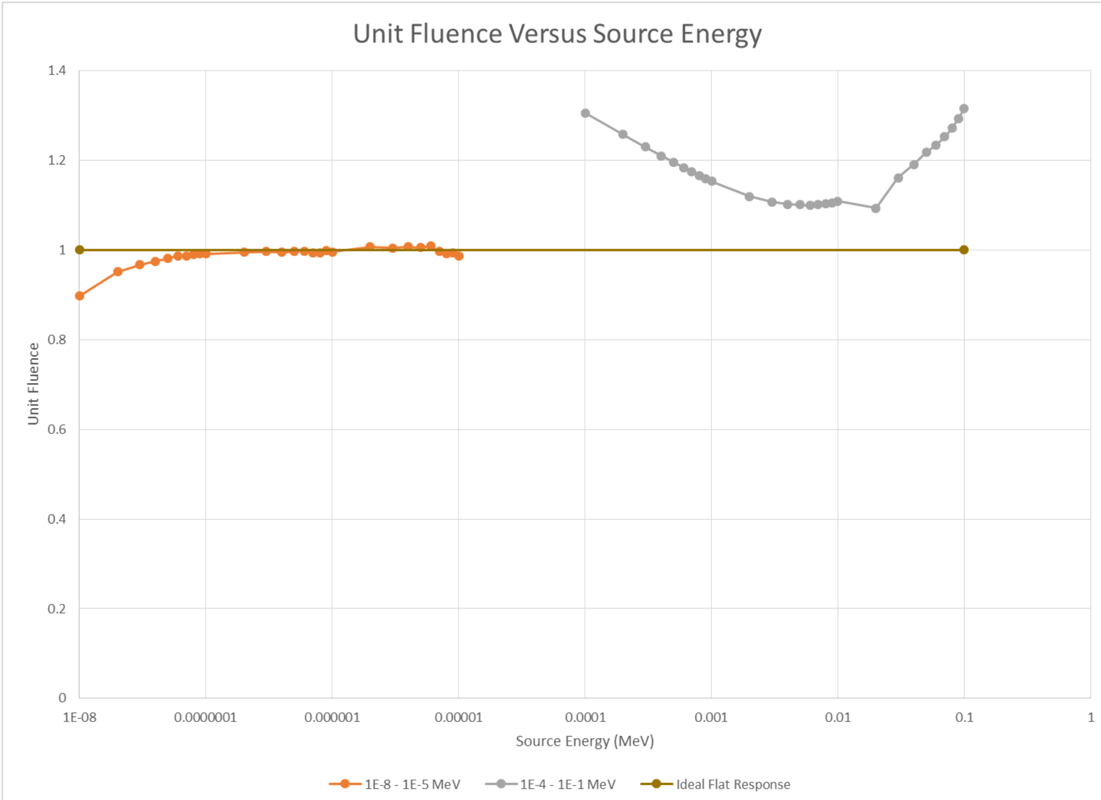

Figure 23. Unit fluence versus source energy for the 5x25 detector array applied to the following energy ranges: 1E-8 to 1E-5 MeV and 1E-4 to 1E-1 MeV

The weighting values, a_j, were then applied to the reactions-cm^2 data from the moderated and unmoderated sources. The data from the moderated and unmoderated sources were combined with the weighting values for each energy range to see if there was a characteristic response curve when the unit fluence for the source was plotted versus the energy range that the weighted values came from. This is shown in Figure 24 and 25, where the x axis corresponds to the energy range with 1 being 1E-8 to 1E-5 MeV and 5 being 14 to 20 MeV. The unmoderated sources produced characteristic curves while the moderated sources did not.

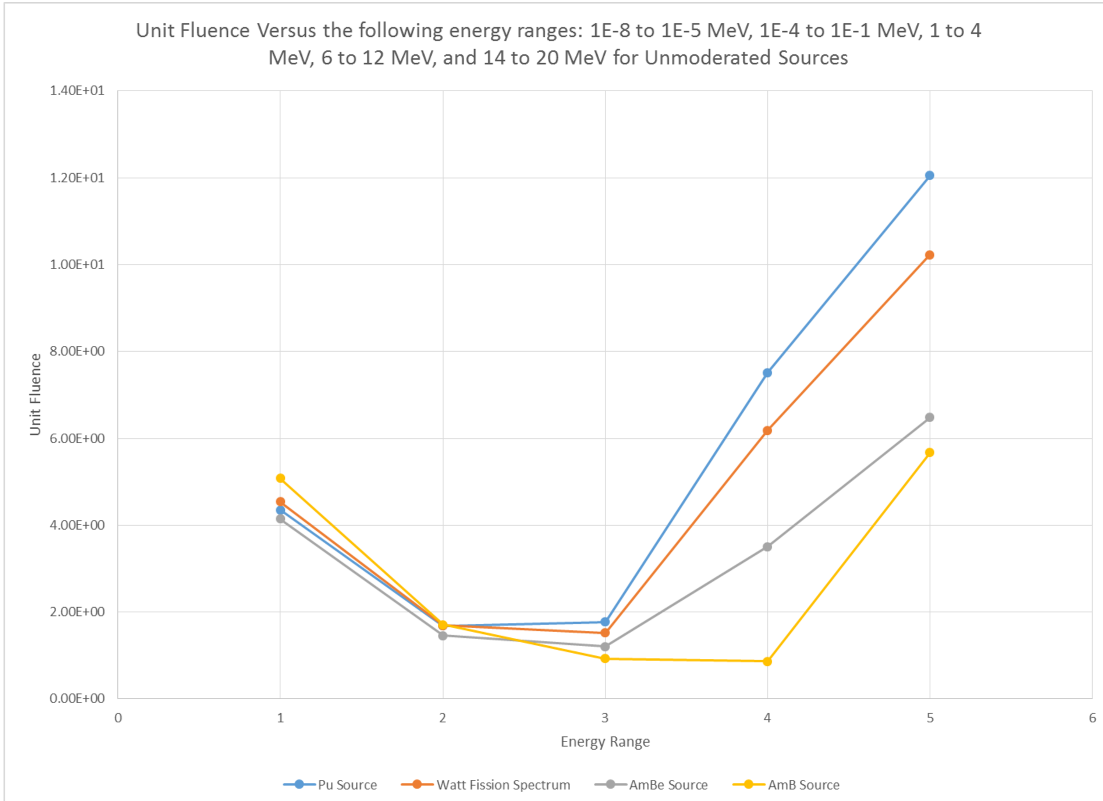

Figure 24. Unit fluence versus the following energy ranges: 1E-8 to 1E-5 MeV, 1E-4 to 1E-1 MeV, 1 to 4 MeV, 6 to 12 MeV, and 14 to 20 MeV for unmoderated sources

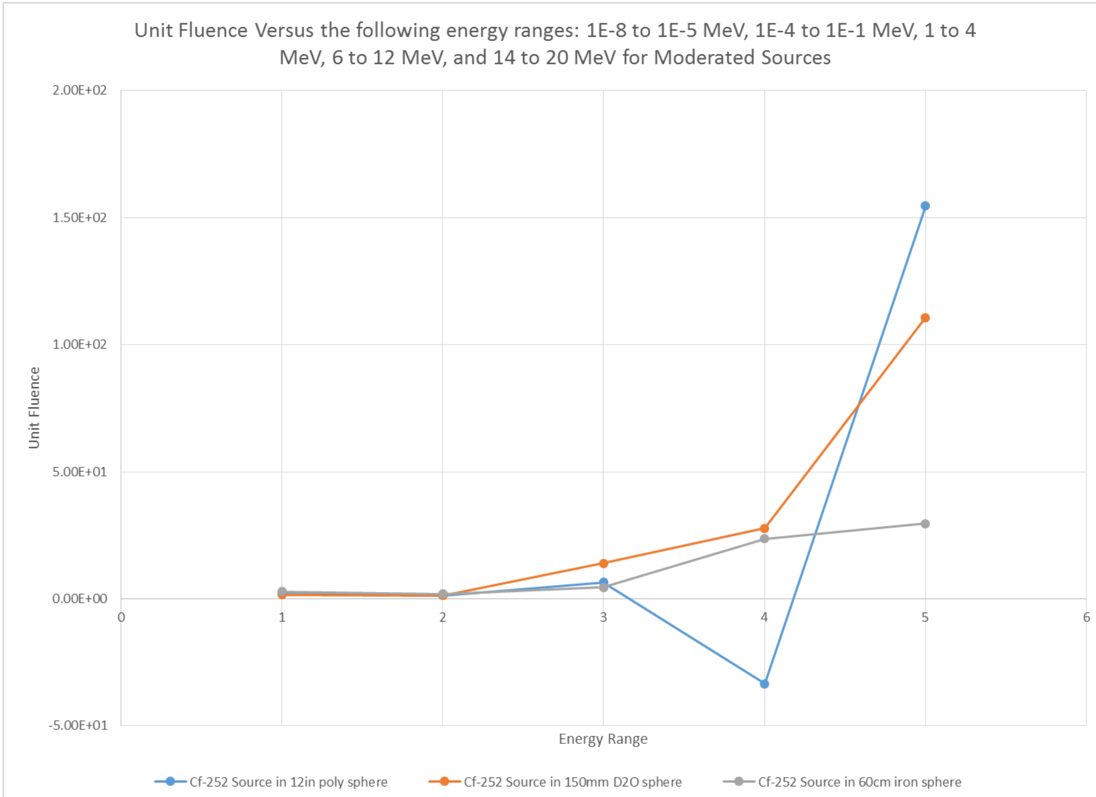

Figure 25. Unit fluence versus the following energy ranges: 1E-8 to 1E-5 MeV, 1E-4 to 1E-1 MeV, 1 to 4 MeV, 6 to 12 MeV, and 14 to 20 MeV for moderated sources

3.6 COMPARISION OF 5X25 DETECTOR ARRAY AND BONNER SPHERES

The method of using Bonner spheres to detect neutrons is the basis that was used in the design of this final detector array. The length of the final 5x25 detector array is 100 cm. If Bonner spheres corresponding to the size of each moderator height used in the 5x25 detector array were set side by side, then the length of those Bonner spheres would be 146.15 cm. This length was calculated by taking Bonner spheres with the following radii: 2.545, 3.18, 3.815, 5.72, 6.355, 6.99, 10.165, 10.8, 11.435, 12.07 and placing them side by side. The weight of the final 5x25 detector array is 12.08 kg or 26.64 pounds. The weight of the Bonner spheres described earlier is 25.21 kg or 55.58 pounds.

The responses for each detector in the array were also analyzed. Using symmetry similar detectors' responses were averaged in each panel. This produced a total of seven values for the average reactions-cm^2 in each panel for a total of 35 values at each source energy level. The averages were also summed to give the total average reactions-cm^2 for the 5x25 detector array by source energy. The results were plotted versus source energy in the figures below. Panel 1 is the 5x5 detector array for the 1E-8 to 1E-5 MeV energy range. Panel 2 is the 5x5 detector array for the 1E-4 to 1E-1 MeV energy range. Panel 3 is the 5x5 detector array for the 1 to 4 MeV energy range. Panel 4 is the 5x5 detector array for the 6 to 12 MeV energy range. Panel 5 is the 5x5 detector array for the 14 to 20 MeV energy range. Figure 32 shows Bonner response curves from the Davidson and Hertel paper.[17]

Figures 26 through 30 show that the average response from similar detector units are less than the Bonner sphere responses shown in Figure 32. The response curves are similar in shape for detector units of similar sizes when compared to Bonner sphere response curves of Bonner spheres of similar size. When the average responses for the detector units of the 5x25 detector array are summed together, the response is greater than the Bonner spheres. It also gives a characteristic curve shape that is similar to a curve that would be generated by combining the highest responses from the different Bonner spheres across all energies.

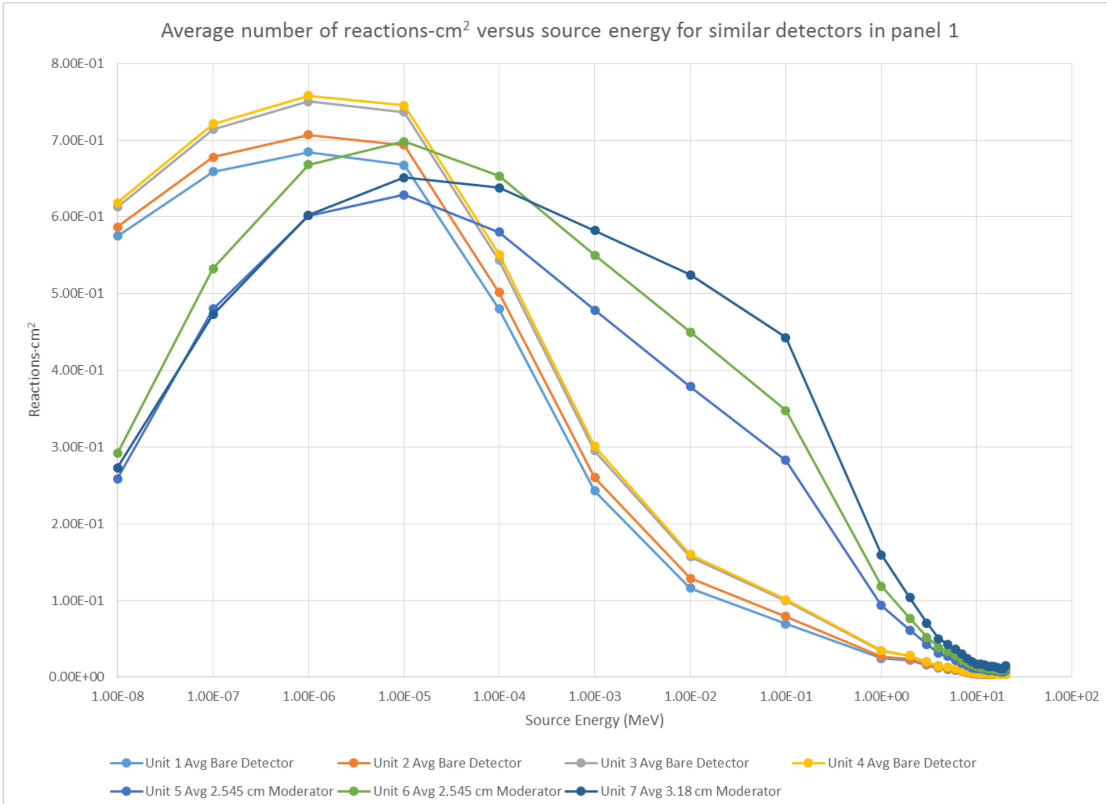

Figure 26. Average number of reactions-cm^2 versus source energy for similar detectors in panel 1

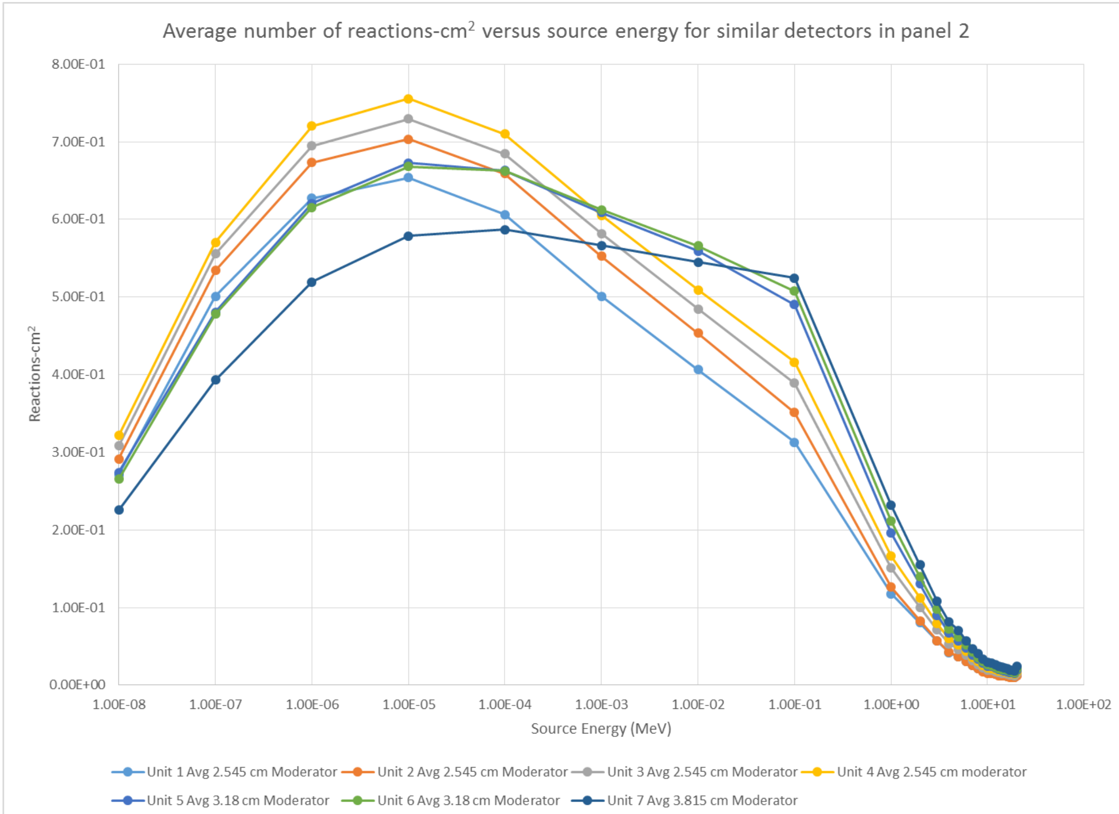

Figure 27. Average number of reactions-cm^2 versus source energy for similar detectors in panel 2

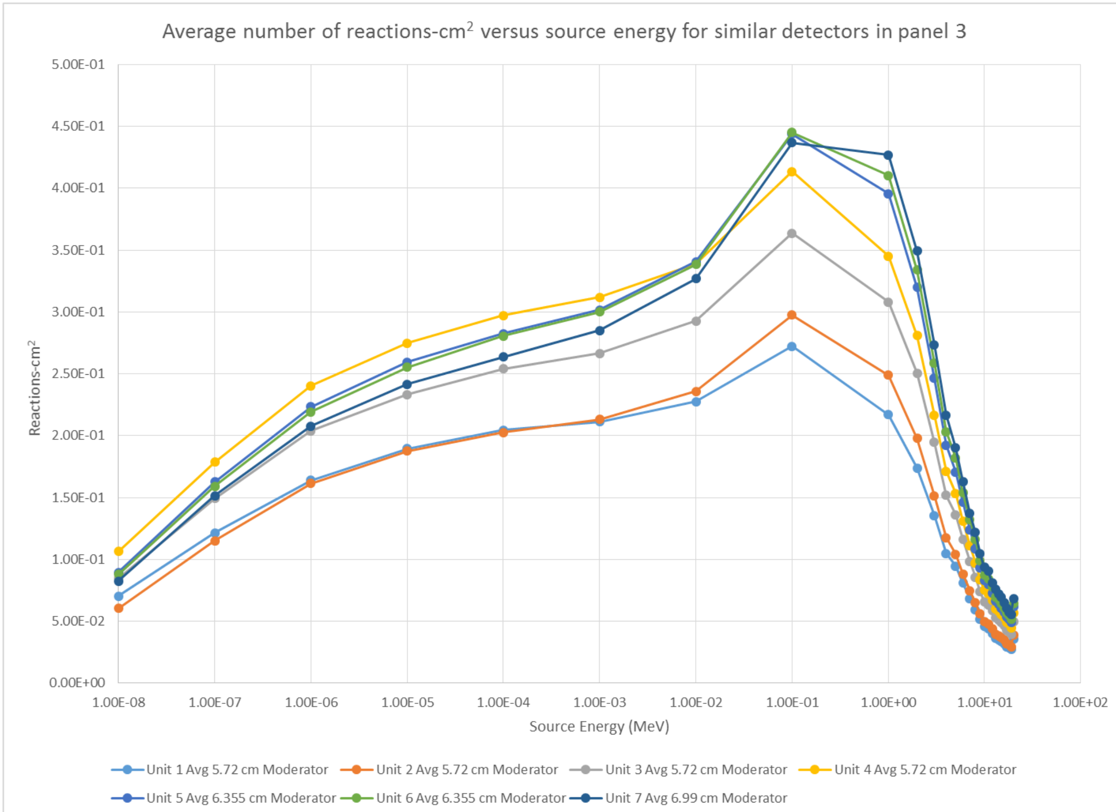

Figure 28. Average number of reactions-cm^2 versus source energy for similar detectors in panel 3

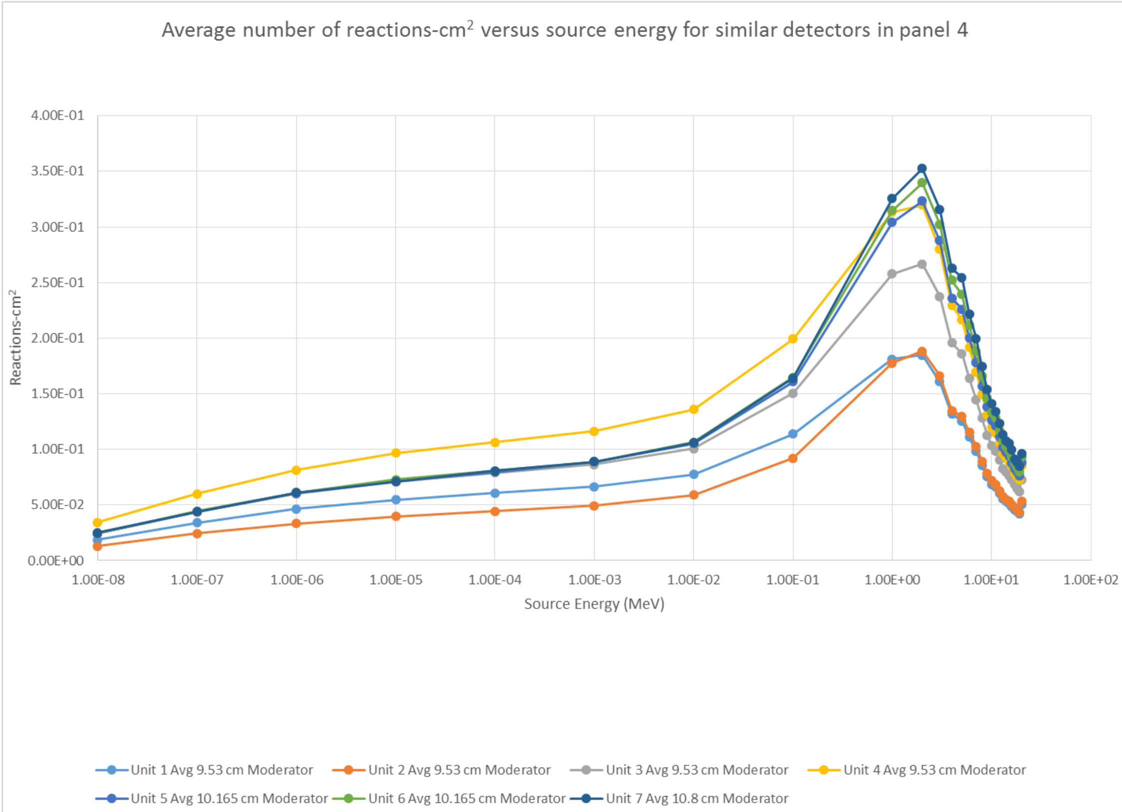

Figure 29. Average number of reactions-cm^2 versus source energy for similar detectors in panel 4

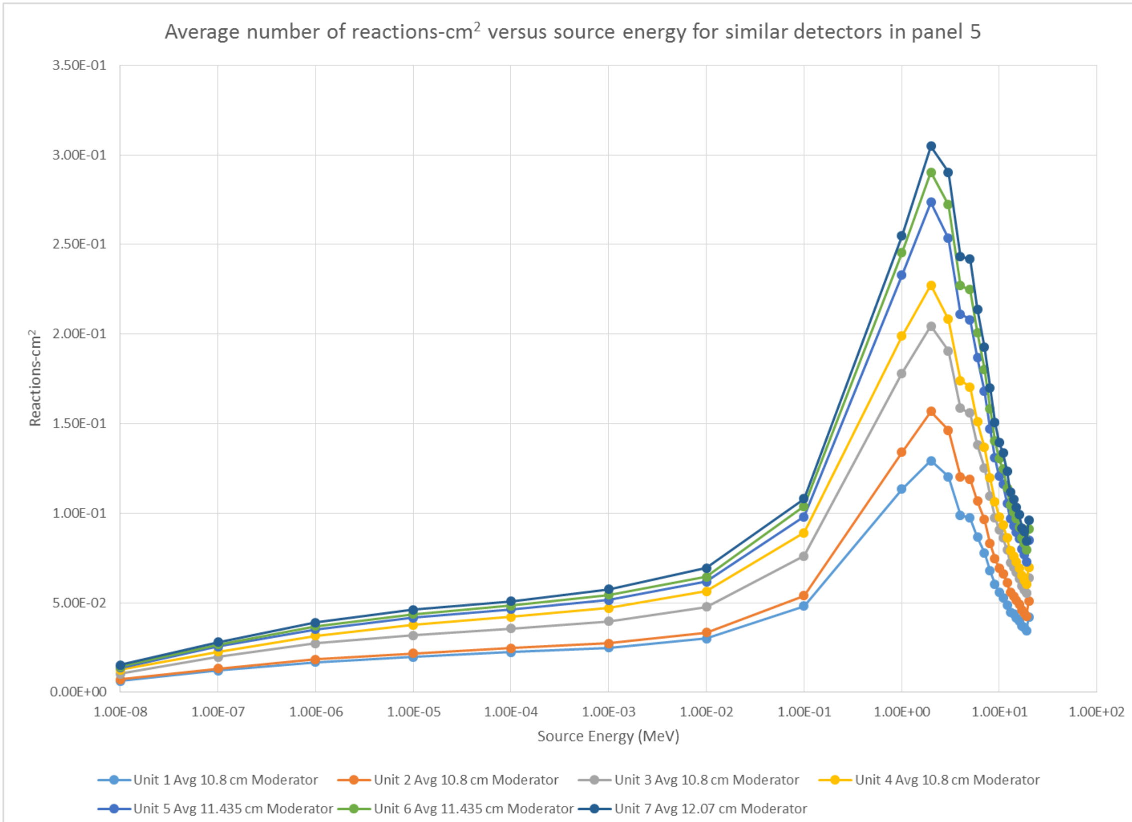

Figure 30. Average number of reactions-cm^2 versus source energy for similar detectors in panel 5

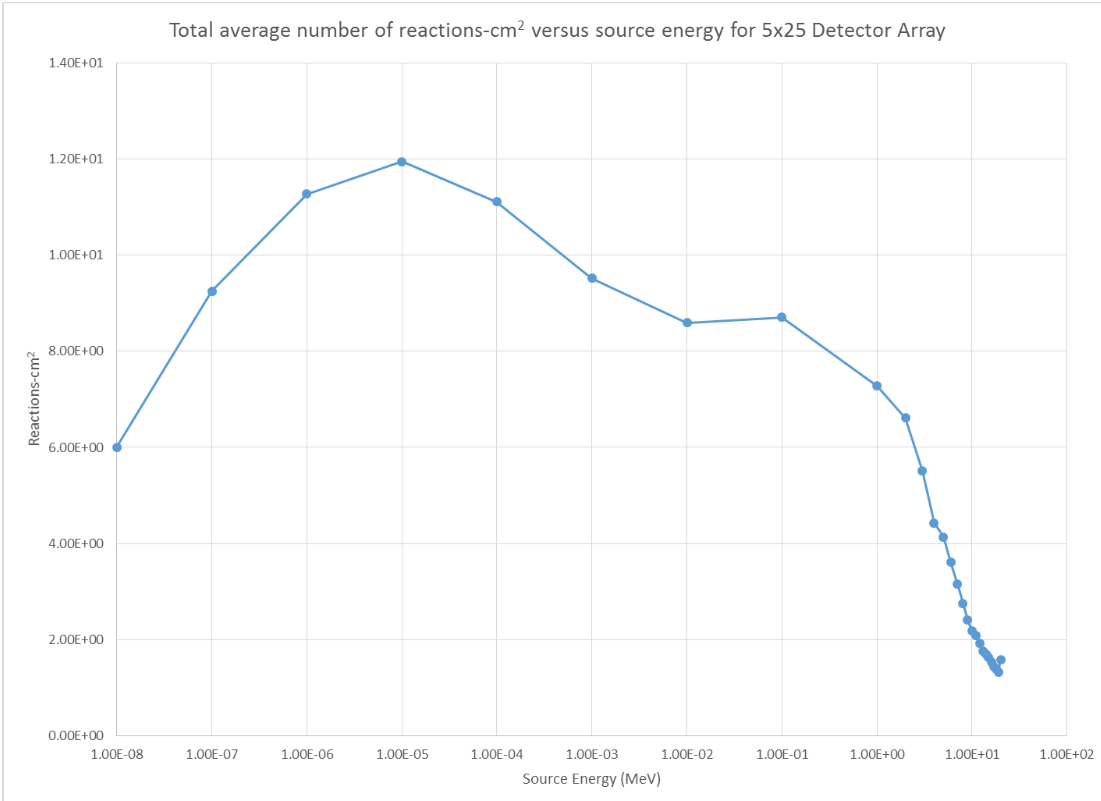

Figure 31. Total Average number of reactions-cm^2 versus source energy for 5x25 Detector Array

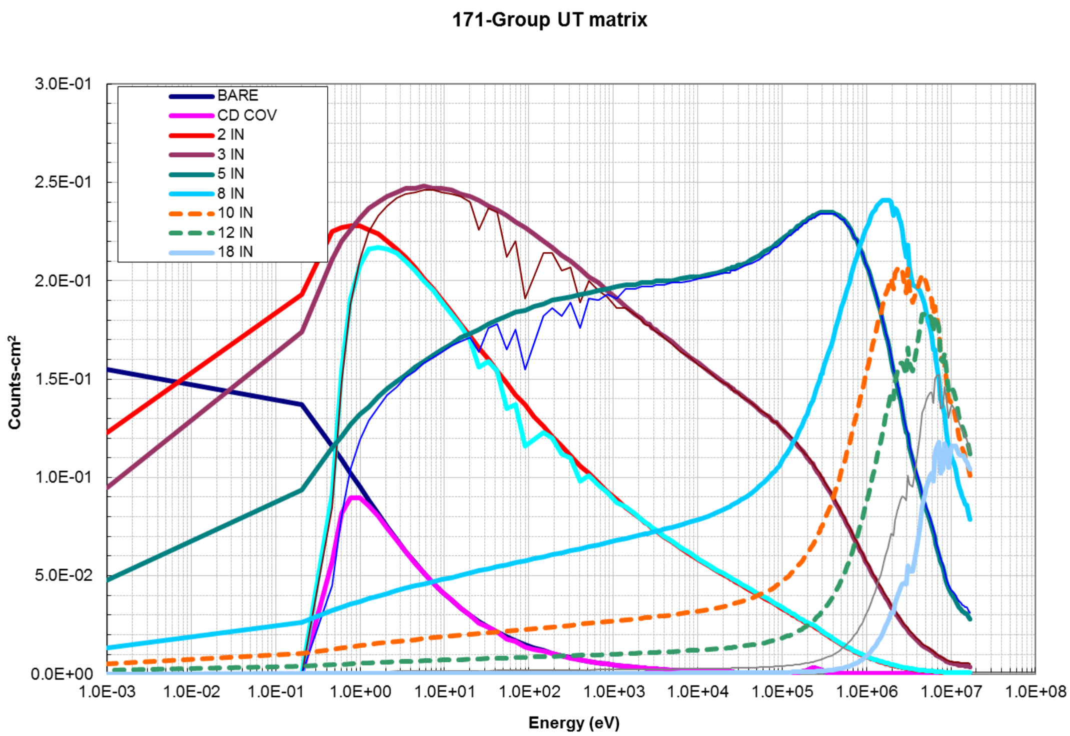

Figure 32. Bonner sphere response curves from Davidson and Hertel paper[17]

The same averaging method was applied to the data obtained from the moderated and unmoderated sources. The average responses were plotted for each panel for each similar detector unit model to determine if a characteristic curve was generated. The unmoderated sources generated characteristic curves in each panel. The moderated sources generated characteristic curves in all panels except for the first panel that covers the 1E-8 to 1E-5 MeV energy range. These graphs are shown in the Figures 33 through 42.

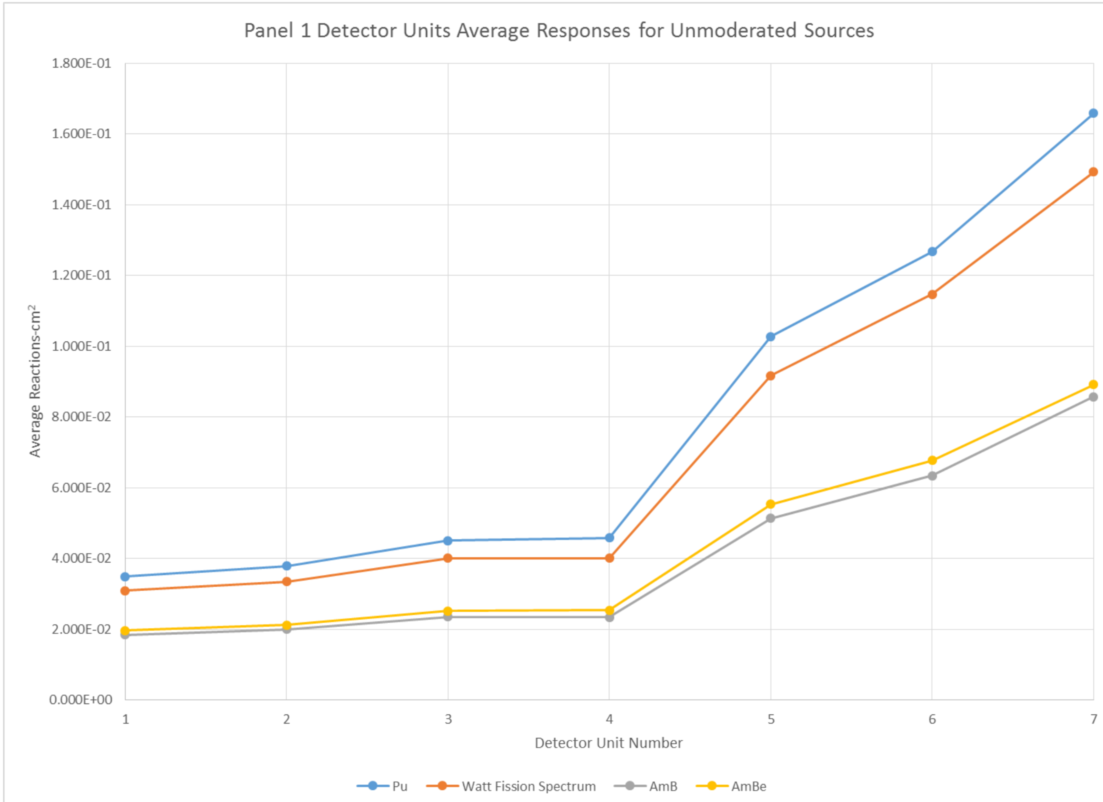

Figure 33. Panel 1 detector units average responses for unmoderated sources

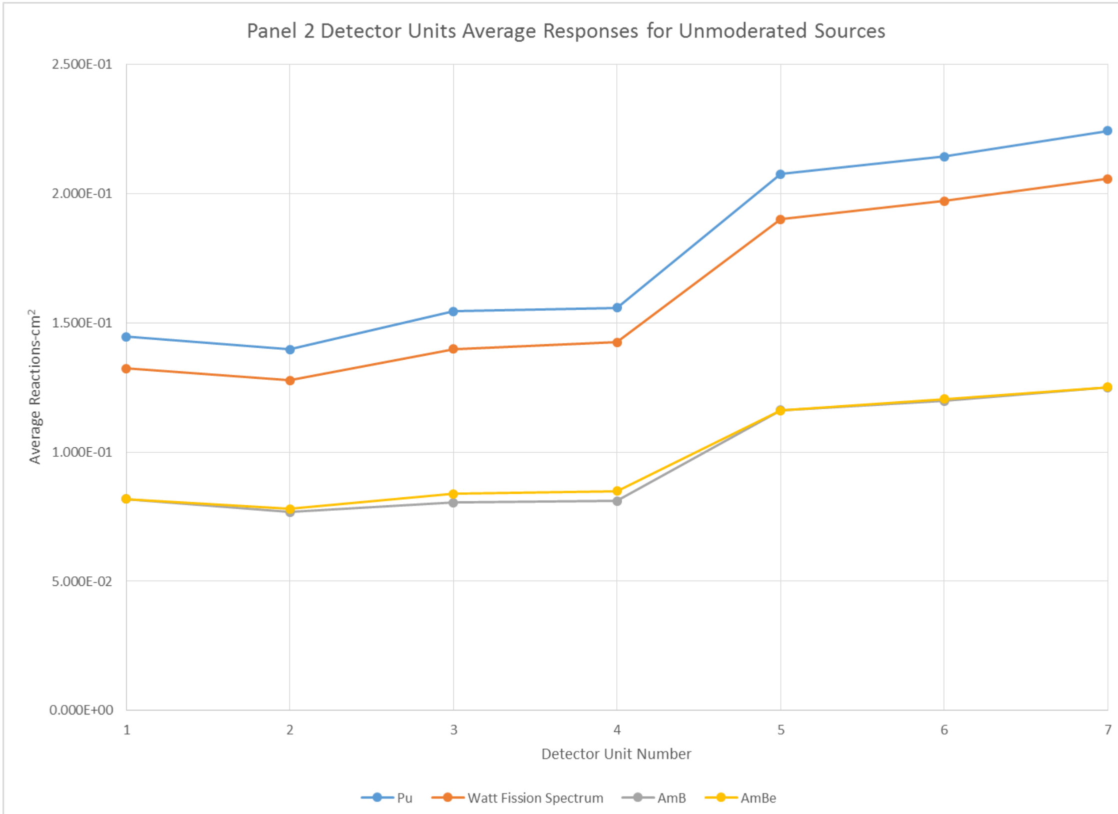

Figure 34. Panel 2 detector units average responses for unmoderated sources

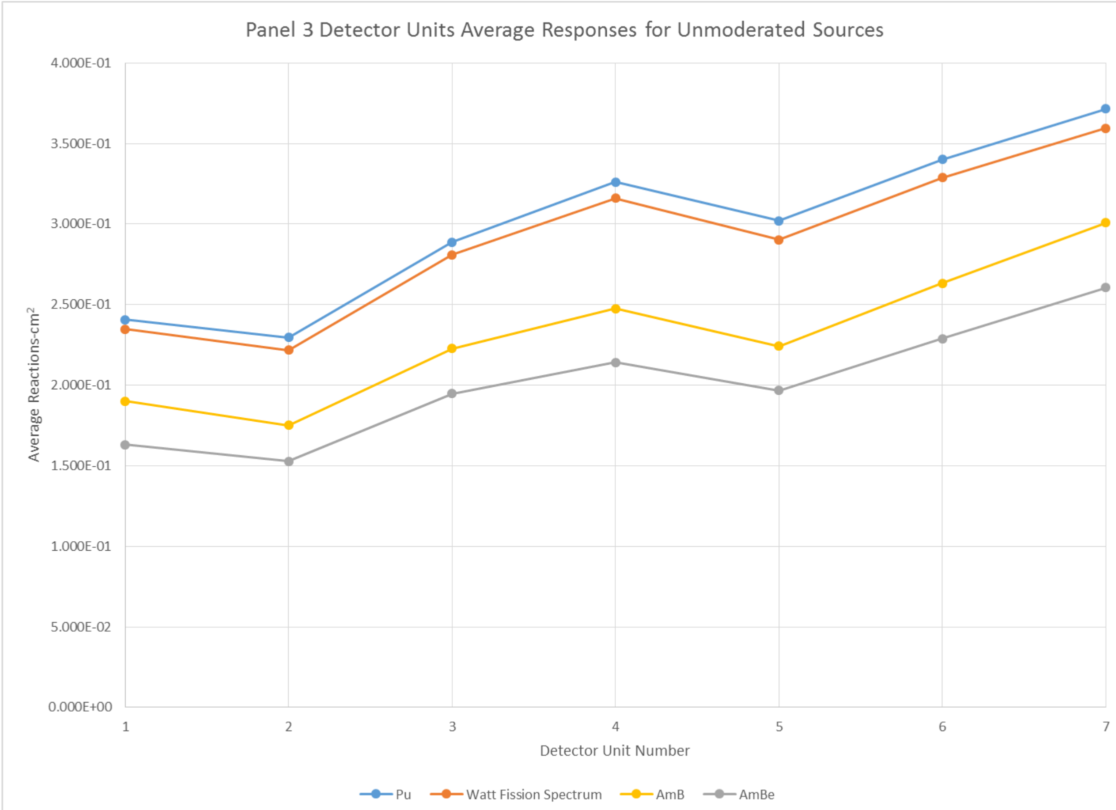

Figure 35. Panel 3 detector units average responses for unmoderated sources

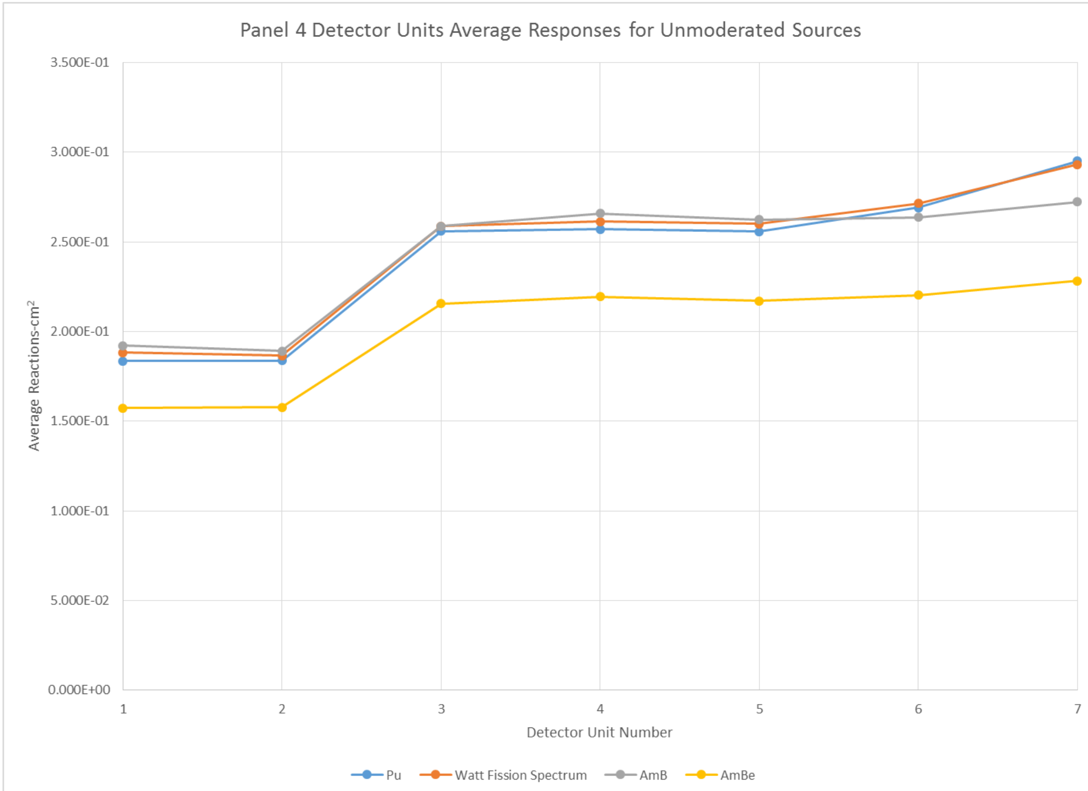

Figure 36. Panel 4 detector units average responses for unmoderated sources

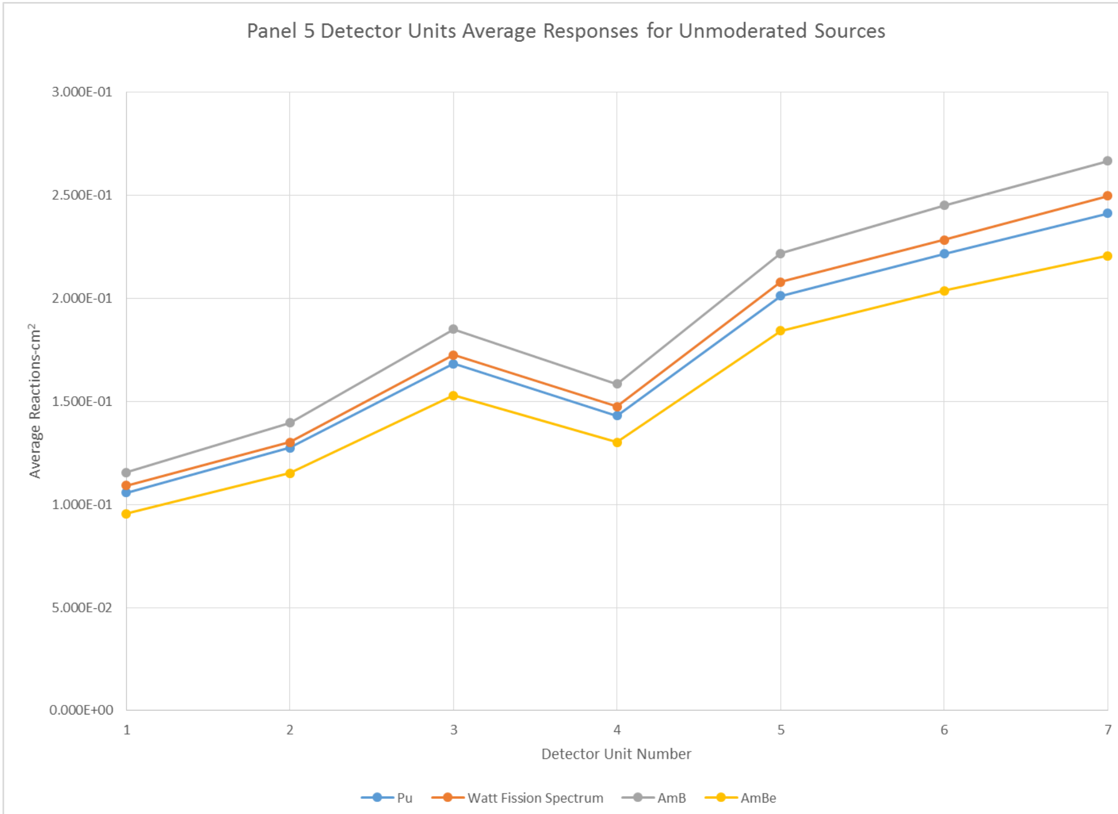

Figure 37. Panel 5 detector units average responses for unmoderated sources

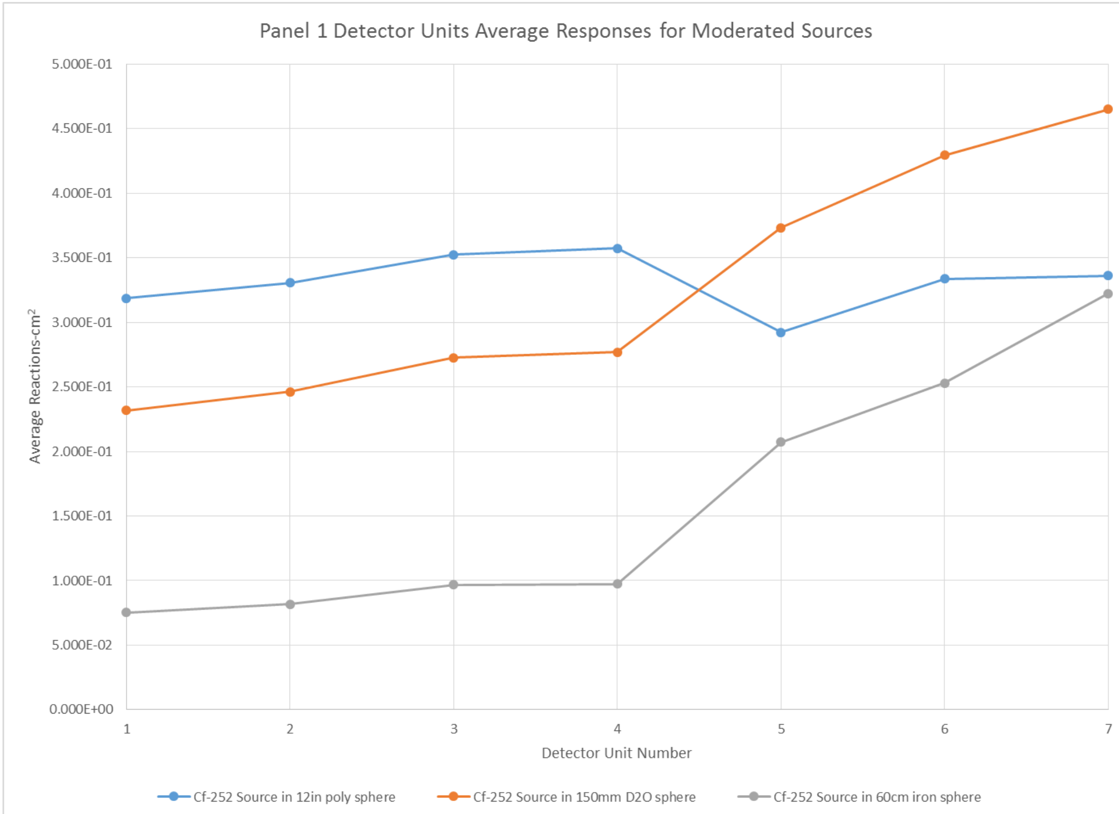

Figure 38. Panel 1 detector units average responses for moderated sources

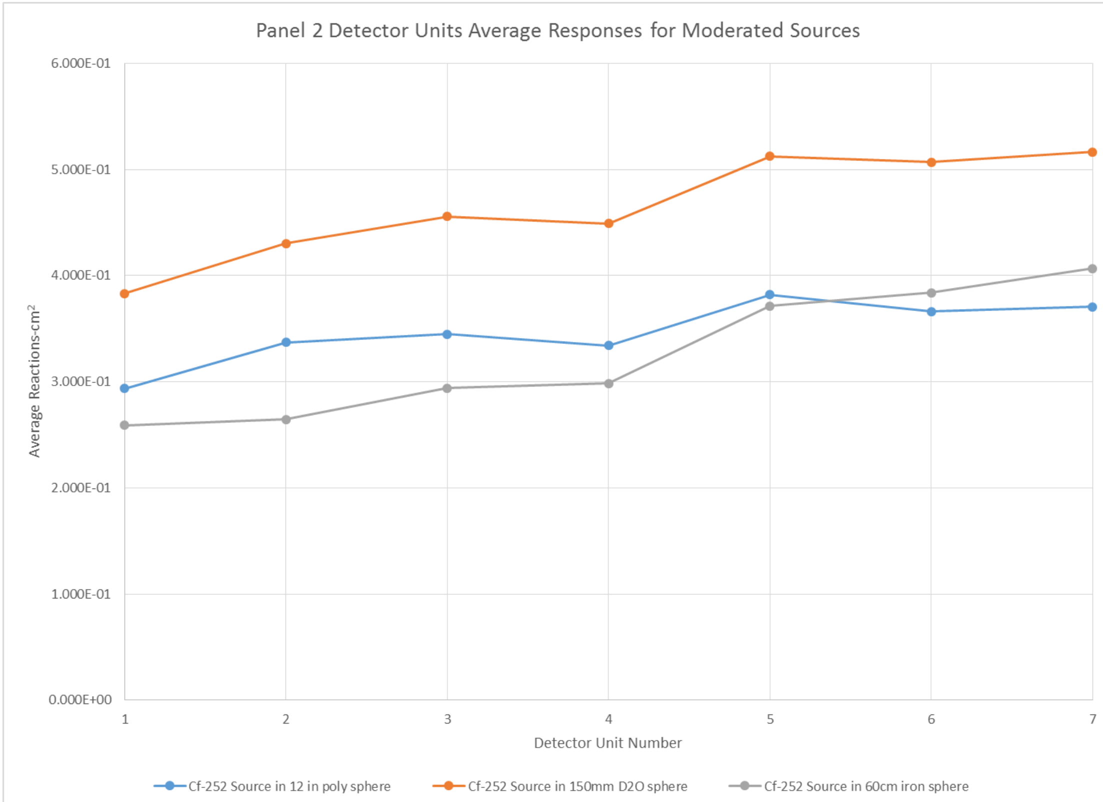

Figure 39. Panel 2 detector units average responses for moderated sources

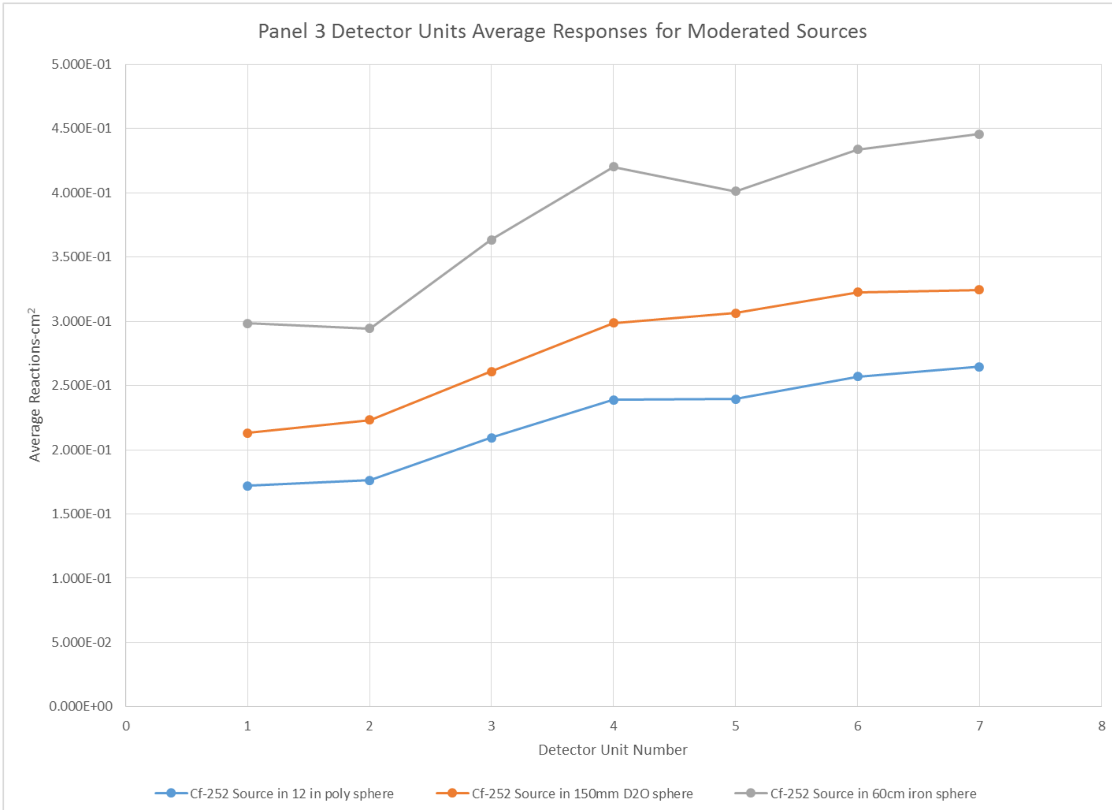

Figure 40. Panel 3 detector units average responses for moderated sources

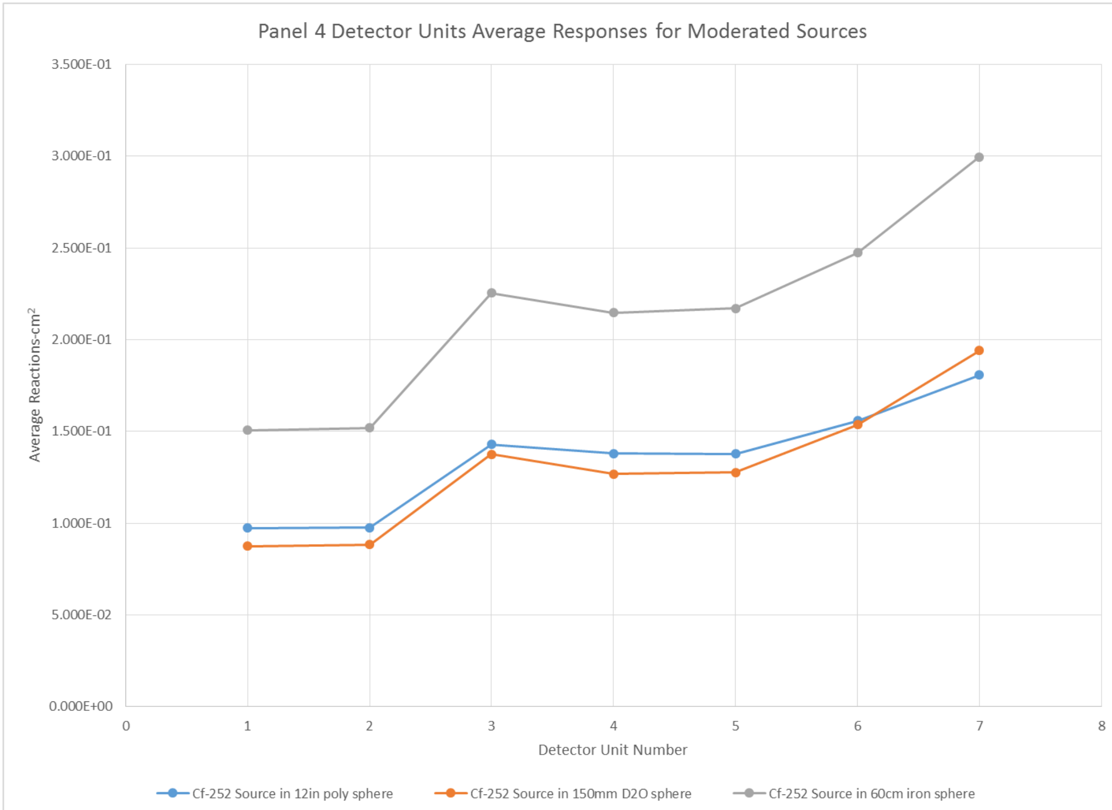

Figure 41. Panel 4 detector units average responses for moderated sources

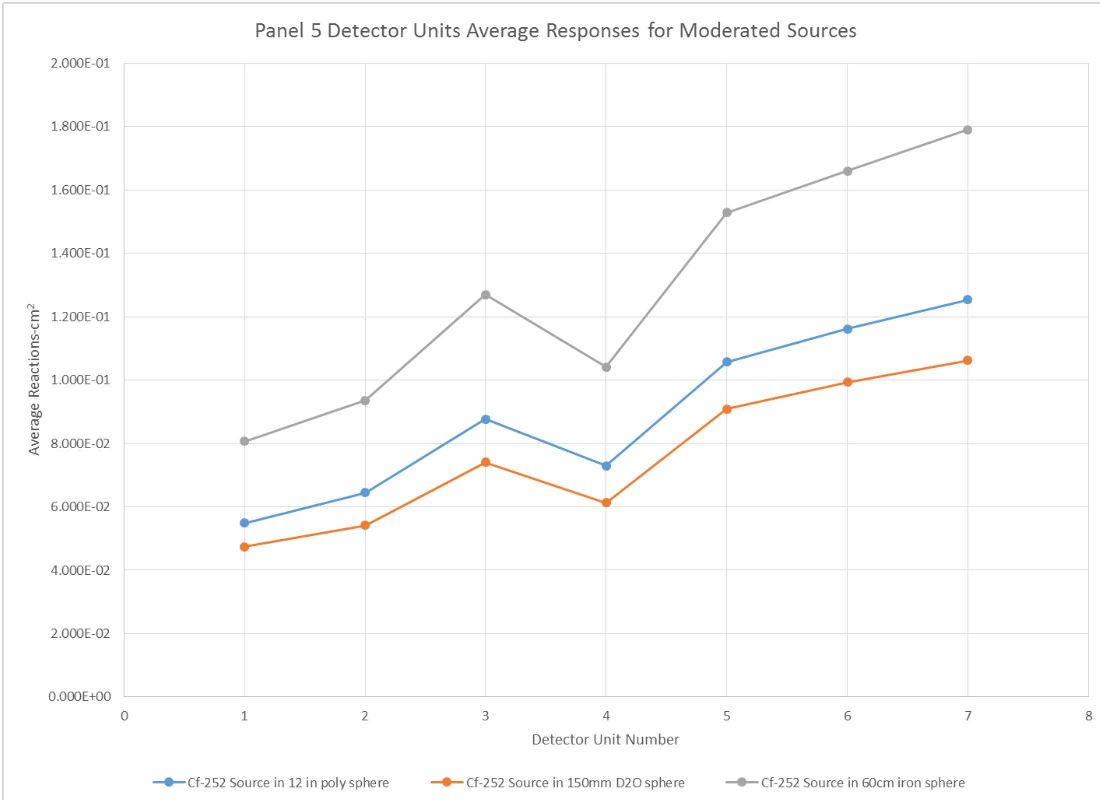

Figure 42. Panel 5 detector units average responses for moderated sources

CHAPTER 4

CONCLUSIONS AND FUTURE WORK

4.1 Conclusions

The data show that given thermal neutron detectors covered with flat polyethylene moderators of different thicknesses mounted on a panel can be used to create a detector system that has energy sensitivity. Using four different detector array configurations, it is possible to determine a detector array that can provide neutron energy information. The MCNP simulations conducted showed that among the configurations tested, the pyramid model was the most successful configuration over the widest energy ranges. A 5x25 detector array that consisted of five different pyramid models was investigated. The panels were selected based on the sensitivities to five energy ranges. Adding a 2.54 cm polyethylene layer behind the detector array increased the number of reaction-cm^2 as a result of neutron backscatter. Adding an additional 5x5 detector array with a layer of beryllium increased the number of reactions per neutron fluence above 1 MeV. The 5x25 detector array produced a similar distribution of reactions for unmoderated neutron spectra tested. The 5x25 detector array produced a similar distribution of reactions for moderated neutron spectra tested. These characteristic distributions could be used to detect SNM. The final 5x25 detector array design is lighter and smaller than an array of similarly sized Bonner spheres. The overall response of the 5x25 gives a higher response over an energy range than a single Bonner sphere. The average responses in similar detector units in different panels give a response curve that is similar to a Bonner sphere response curve. The average responses in similar detector units in different panels for moderated and unmoderated spectra produces characteristic curves in each panel that could be used to identify fission sources. This detector design in this work is not going to provide energy spectra, but the application of this detector does not require it to produce detailed spectra. The purpose of this detector is to locate SNM with a relatively high certainty and that can be done by looking at various characteristics of the detection system. Although this work did not yield the optimum configuration, it provided insight to direct future work to find the optimal configuration.

4.2 Future Work

The research described in this work is only based on simulation. An actual physical detector array may or may not behave exactly like the simulations, but the first steps of demonstrating the feasibility of designing an energy-dependent neutron detector array that could be used to detect special nuclear materials have been demonstrated. Future work would include further simulations on the configuration designs of the 5x5 detector arrays. Such simulations could explore other moderator configuration designs such as a moderators with larger cross section areas such as an 8 cm by 8 cm moderator face, explore the effects of placing the detectors on moderator boundaries, and placing the moderator surfaces at various angles. Further work could also be done on the 5x25 moderator design by increasing the number of models used in the design, conducting simulations with the source at various distances, modeling the source in buildings, and modeling the detector moving at various speeds. There could also be further research on the size and configuration of the beryllium layer and moderator to see if it is possible to further increase the number of high energy neutrons detected. Also, boron might be incorporated into the thinner moderators to reduce the low energy response. This could possibly improve the overall system capabilities by decreasing the response at low energies to give a flatter response curve.

There are some important factors that must be added to future simulations to make them more realistic. The simulations conducted in this work were done under ideal conditions. The air in the simulation was modeled as dry air with nothing that would interact significantly with the neutrons. Background radiation was not included in the simulations. The ground was not modeled in the simulations; so there was no accounting for reflection off the ground surface. Future simulations will have to take these factors into account for a realistic result.

Material research can also be done for the moderator to determine if different materials would better moderate neutrons of different energies. Also, further analysis can be done on different neutron detectors to determine the best type of detector to be used, and perhaps a combination of different neutron detectors to provide the best response from the detector array. There is also work that needs to be done with the approach to create a response equation that would produce a flat response in the detector array given energy ranges. There is much more simulation work that needs to be done before a prototype detector array can be built and tested under real world conditions. If a detector model is simulated with real world conditions successfully, then it would be feasible to build a prototype detector. The concept of a multi-energy neutron detector is possible and would be a great asset to the United States Government in the effort to stop proliferation of SNM.

APPENDIX A

5X5 DETECTOR ARRAYS TOTAL NUMBER OF REACTIONS PER NEUTRON BY SOURCE ENERGY

The highest number of reactions per neutron by source energy is highlighted in yellow.

Pyramid Mode

Table 4. Total Number of Reactions per Neutron by Source Energy for the Pyramid Model

Source Energy	1E-8 MeV	2.5E-8 MeV	5E-8 MeV	1E-7 MeV	1E-6 MeV	1E-5 MeV	1E-4 MeV	1E-3 MeV	1E-2 MeV	1E-1 MeV	1 MeV	2 MeV	4 MeV	6 MeV	8 MeV	10 MeV	12 MeV	14 MeV	16 MeV	18 MeV	20 MeV
Model #																					
24	2.907E-02	3.303E-02	3.553E-02	3.764E-02	4.165E-02	4.166E-02	3.305E-02	2.131E-02	1.403E-02	1.009E-02	3.393E-03	2.467E-03	1.280E-03	9.432E-04	6.106E-04	4.521E-04	4.047E-04	3.626E-04			
2	1.707E-02	2.263E-02	2.708E-02	3.109E-02	3.940E-02	4.163E-02	3.965E-02	3.442E-02	2.940E-02	2.405E-02	9.082E-03	5.958E-03	3.061E-03	2.122E-03	1.453E-03	1.054E-03	9.581E-04	8.349E-04			
3	1.236E-02	1.650E-02	1.990E-02	2.319E-02	3.071E-02	3.334E-02	3.309E-02	3.073E-02	2.859E-02	2.646E-02	1.173E-02	7.949E-03	4.138E-03	2.949E-03	2.080E-03	1.498E-03	1.341E-03	1.164E-03			
4	9.130E-03	1.220E-02	1.478E-02	1.736E-02	2.362E-02	2.629E-02	2.688E-02	2.624E-02	2.604E-02	2.671E-02	1.435E-02	9.777E-03	5.226E-03	3.744E-03	2.682E-03	1.997E-03	1.779E-03	1.557E-03			
5	6.840E-03	9.137E-03	1.107E-02	1.305E-02	1.800E-02	2.052E-02	2.145E-02	2.171E-02	2.265E-02	2.544E-02	1.589E-02	1.152E-02	6.333E-03	4.608E-03	3.285E-03	2.477E-03	2.230E-03	1.950E-03			
6	5.178E-03	6.896E-03	8.372E-03	9.857E-03	1.372E-02	1.588E-02	1.699E-02	1.765E-02	1.907E-02	2.312E-02	1.702E-02	1.289E-02	7.231E-03	5.403E-03	3.841E-03	2.895E-03	2.594E-03	2.280E-03			
7	3.941E-03	5.266E-03	6.393E-03	7.502E-03	1.052E-02	1.227E-02	1.334E-02	1.409E-02	1.572E-02	2.021E-02	1.739E-02	1.387E-02	8.137E-03	6.091E-03	4.443E-03	3.347E-03	2.952E-03	2.584E-03			
8	3.037E-03	4.035E-03	4.891E-03	5.731E-03	8.079E-03	9.472E-03	1.041E-02	1.113E-02	1.272E-02	1.726E-02	1.729E-02	1.436E-02	8.787E-03	6.653E-03	4.909E-03	3.671E-03	3.303E-03	2.874E-03			
9	2.342E-03	3.108E-03	3.772E-03	4.401E-03	6.213E-03	7.293E-03	8.067E-03	8.735E-03	1.016E-02	1.441E-02	1.670E-02	1.457E-02	9.146E-03	7.088E-03	5.247E-03	3.996E-03	3.534E-03	3.072E-03			
10	1.813E-03	2.394E-03	2.888E-03	3.398E-03	4.803E-03	5.662E-03	6.256E-03	6.869E-03	8.044E-03	1.185E-02	1.586E-02	1.451E-02	9.413E-03	7.501E-03	5.494E-03	4.262E-03	3.771E-03	3.263E-03			
11	1.389E-03	1.846E-03	2.245E-03	2.620E-03	3.698E-03	4.359E-03	4.870E-03	5.353E-03	6.339E-03	9.623E-03	1.474E-02	1.408E-02	9.388E-03	7.716E-03	5.728E-03	4.494E-03	3.943E-03	3.439E-03			
12	1.077E-03	1.436E-03	1.723E-03	2.023E-03	2.864E-03	3.382E-03	3.784E-03	4.181E-03	4.961E-03	7.748E-03	1.345E-02	1.355E-02	9.272E-03	7.693E-03	5.869E-03	4.661E-03	4.126E-03	3.570E-03			
13	8.278E-04	1.108E-03	1.344E-03	1.574E-03	2.223E-03	2.617E-03	2.932E-03	3.235E-03	3.883E-03	6.131E-03	1.207E-02	1.282E-02	9.110E-03	7.740E-03	5.905E-03	4.852E-03	4.251E-03	3.739E-03			
14	6.463E-04	8.656E-04	1.042E-03	1.225E-03	1.723E-03	2.029E-03	2.274E-03	2.529E-03	3.023E-03	4.850E-03	1.085E-02	1.196E-02	8.944E-03	7.692E-03	6.013E-03	4.859E-03	4.281E-03	3.804E-03	3.412E-03	3.078E-03	3.581E-03
15	5.074E-04	6.767E-04	8.038E-04	9.505E-04	1.332E-03	1.576E-03	1.757E-03	1.974E-03	2.346E-03	3.813E-03	9.570E-03	1.117E-02	8.678E-03	7.577E-03	5.950E-03	4.849E-03	4.295E-03	3.883E-03	3.488E-03	3.082E-03	3.592E-03
16	3.885E-04	5.216E-04	6.235E-04	7.352E-04	1.035E-03	1.230E-03	1.377E-03	1.534E-03	1.844E-03	3.013E-03	8.342E-03	1.036E-02	8.288E-03	7.428E-03	5.888E-03	4.947E-03	4.295E-03	3.877E-03	3.483E-03	3.132E-03	3.553E-03
17	3.025E-04	4.062E-04	4.885E-04	5.785E-04	7.972E-04	9.461E-04	1.072E-03	1.191E-03	1.437E-03	2.364E-03	7.195E-03	9.444E-03	7.715E-03	7.191E-03	5.720E-03	4.847E-03	4.329E-03	3.842E-03	3.513E-03	3.134E-03	3.558E-03
18	2.378E-04	3.152E-04	3.784E-04	4.456E-04	6.248E-04	7.466E-04	8.289E-04	9.254E-04	1.126E-03	1.855E-03	6.234E-03	8.531E-03	7.368E-03	6.975E-03	5.600E-03	4.801E-03	4.257E-03	3.816E-03	3.399E-03	3.137E-03	3.536E-03
19	1.858E-04	2.494E-04	2.955E-04	3.474E-04	4.878E-04	5.805E-04	6.429E-04	7.240E-04	8.802E-04	1.446E-03	5.354E-03	7.724E-03	6.917E-03	6.713E-03	5.444E-03	4.670E-03	4.242E-03	3.729E-03	3.385E-03	3.098E-03	3.438E-03
20	1.422E-04	1.951E-04	2.307E-04	2.729E-04	3.805E-04	4.516E-04	5.008E-04	5.646E-04	6.819E-04	1.133E-03	4.627E-03	6.944E-03	6.430E-03	6.507E-03	5.265E-03	4.610E-03	4.153E-03	3.710E-03	3.362E-03	3.073E-03	3.334E-03
21	1.097E-04	1.468E-04	1.772E-04	2.043E-04	2.837E-04	3.394E-04	3.786E-04	4.222E-04	5.087E-04	8.447E-04	3.733E-03	5.895E-03	5.763E-03	5.942E-03	4.882E-03	4.395E-03	3.908E-03	3.524E-03	3.245E-03	2.945E-03	3.203E-03

Concave Model

Table 5. Total Number of Reactions per Neutron by Source Energy for the Concave Model

Source Energy	1E-8 MeV	2.5E-8 MeV	5E-8 MeV	1E-7 MeV	1E-6 MeV	1E-5 MeV	1E-4 MeV	1E-3 MeV	1E-2 MeV	1E-1 MeV	1 MeV	2 MeV	4 MeV	6 MeV	8 MeV	10 MeV	12 MeV	14 MeV	16 MeV	18 MeV	20 MeV
Concave Model #																					
3	1.629E-02						3.665E-02				8.149E-03		2.804E-03		1.363E-03	9.834E-04		7.812E-04		6.331E-04	
4	1.175E-02						3.145E-02				1.123E-02		3.910E-03		1.947E-03	1.418E-03		1.113E-03		9.167E-04	
5	8.824E-03						2.577E-02				1.321E-02		5.033E-03		2.519E-03	1.887E-03		1.497E-03		1.202E-03	
6	6.685E-03						2.083E-02				1.505E-02		6.043E-03		3.131E-03	2.350E-03		1.860E-03		1.483E-03	
7	5.116E-03						1.661E-02				1.616E-02		6.043E-03		3.768E-03	2.809E-03		2.180E-03		1.741E-03	
8	3.944E-03						1.316E-02				1.675E-02		7.894E-03		4.241E-03	3.200E-03		2.524E-03		1.987E-03	
9	3.064E-03						1.035E-02				1.656E-02		8.564E-03		4.748E-03	3.594E-03		2.782E-03		2.256E-03	
10	2.391E-03						8.103E-03				1.620E-02		8.964E-03		5.139E-03	3.877E-03		3.032E-03		2.492E-03	
11											1.550E-02		9.181E-03		5.409E-03	4.166E-03		3.239E-03		2.695E-03	
12											1.446E-02		9.272E-03		5.609E-03	4.447E-03		3.392E-03	3.088E-03	2.771E-03	3.344E-03
13											1.317E-02		9.235E-03		5.839E-03	4.653E-03		3.576E-03	3.211E-03	2.895E-03	3.476E-03
14											1.199E-02		9.162E-03		5.943E-03	4.697E-03		3.694E-03	3.305E-03	3.001E-03	3.452E-03
15											1.072E-02		8.894E-03		5.875E-03	4.848E-03		3.781E-03	3.346E-03	3.056E-03	3.565E-03
16											9.550E-03		8.604E-03		5.961E-03	4.863E-03		3.837E-03	3.434E-03	3.106E-03	3.562E-03
17											8.361E-03		8.211E-03		5.909E-03	4.817E-03		3.865E-03	3.496E-03	3.122E-03	3.559E-03
18											7.247E-03		7.870E-03		5.820E-03	4.941E-03		3.846E-03	3.430E-03	3.159E-03	3.547E-03
19											6.264E-03		7.368E-03		5.645E-03	4.824E-03		3.831E-03	3.492E-03	3.130E-03	3.475E-03
20											5.418E-03		6.943E-03		5.413E-03	4.682E-03		3.783E-03	3.439E-03	3.087E-03	3.402E-03
21											4.634E-03		6.506E-03		5.193E-03	4.559E-03		3.637E-03	3.326E-03	3.041E-03	3.382E-03
22											3.966E-03		6.011E-03		5.052E-03	4.518E-03		3.627E-03	3.249E-03	3.009E-03	3.342E-03
23											2.192E-03		4.011E-03		3.846E-03	3.647E-03		3.011E-03	2.802E-03	2.528E-03	2.788E-03

Wedge Model

Table 6. Total Number of Reactions per Neutron by Source Energy for the Wedge Model

Source Energy	1E-8 MeV	2.5E-8 MeV	5E-8 MeV	1E-7 MeV	1E-6 MeV	1E-5 MeV	1E-4 MeV	1E-3 MeV	1E-2 MeV	1E-1 MeV	1 MeV	2 MeV	4 MeV	6 MeV	8 MeV	10 MeV	12 MeV	14 MeV	16 MeV	18 MeV	20 MeV
Wedge Model #																					
24	1.727E-02						3.180E-02				9.153E-03		3.224E-03		1.569E-03	1.185E-03					
2	1.137E-02						2.989E-02				1.244E-02		4.601E-03		2.318E-03	1.664E-03					
3	8.395E-03						2.443E-02				1.436E-02		5.610E-03		2.909E-03	2.135E-03					
4	6.299E-03						1.962E-02				1.585E-02		6.517E-03		3.455E-03	2.622E-03					
5	4.779E-03						1.556E-02				1.663E-02		7.472E-03		4.024E-03	3.077E-03					
6	3.656E-03						1.224E-02				1.695E-02		8.175E-03		4.484E-03	3.427E-03					
7							9.601E-03				1.668E-02		8.775E-03		4.926E-03	3.706E-03					
8							7.478E-03				1.603E-02		9.082E-03		5.276E-03	4.078E-03					
9							5.839E-03				1.517E-02		9.274E-03		5.580E-03	4.331E-03					
10							4.526E-03				1.424E-02		9.326E-03		5.768E-03	4.471E-03		3.488E-03	3.118E-03	2.816E-03	3.378E-03
11											1.286E-02		9.183E-03		5.842E-03	4.687E-03		3.637E-03	3.240E-03	2.975E-03	3.472E-03
12											1.152E-02		9.063E-03		5.879E-03	4.765E-03		3.738E-03	3.363E-03	3.042E-03	3.513E-03
13											1.028E-02		8.676E-03		5.931E-03	4.849E-03		3.850E-03	3.409E-03	3.087E-03	3.535E-03
14											9.061E-03		8.383E-03		5.952E-03	4.924E-03		3.821E-03	3.437E-03	3.152E-03	3.601E-03
15											7.913E-03		7.956E-03		5.796E-03	4.848E-03		3.834E-03	3.468E-03	3.074E-03	3.533E-03
16											6.838E-03		7.616E-03		5.661E-03	4.842E-03		3.793E-03	3.460E-03	3.060E-03	3.513E-03
17											6.013E-03		7.210E-03		5.491E-03	4.746E-03		3.795E-03	3.375E-03	3.078E-03	3.482E-03
18											5.068E-03		6.663E-03		5.351E-03	4.646E-03		3.701E-03	3.314E-03	3.116E-03	3.399E-03
19											3.971E-03		5.756E-03		4.822E-03	4.297E-03		3.486E-03	3.206E-03	2.863E-03	3.198E-03

Opposite Wedge Model

Table 7. Total Number of Reactions per Neutron by Source Energy for the Opposite Wedge Model

Source Energy	1E-8 MeV	2.5E-8 MeV	5E-8 MeV	1E-7 MeV	1E-6 MeV	1E-5 MeV	1E-4 MeV	1E-3 MeV	1E-2 MeV	1E-1 MeV	1 MeV	2 MeV	4 MeV	6 MeV	8 MeV	10 MeV	12 MeV	14 MeV	16 MeV	18 MeV	20 MeV
Wedge Model #																					
24	1.769E-02						3.198E-02				8.333E-03		7.414E-03								
2	1.189E-02						3.011E-02				1.208E-02		8.132E-03								
3	8.798E-03						2.457E-02				1.406E-02		8.743E-03								
4	6.602E-03						1.976E-02				1.567E-02		9.061E-03								
5	5.011E-03						1.568E-02				1.648E-02		9.177E-03								
6	3.848E-03						1.234E-02				1.681E-02		9.218E-03								
7	2.958E-03						9.701E-03				1.661E-02		9.107E-03								
8	2.295E-03						7.551E-03				1.605E-02		8.960E-03								
9	1.762E-03						5.864E-03				1.513E-02		8.717E-03								
10	1.359E-03						4.551E-03				1.409E-02		8.393E-03		5.735E-03	4.497E-03		3.472E-03	3.116E-03	2.768E-03	3.358E-03
11													7.984E-03		5.808E-03	4.710E-03		3.604E-03	3.196E-03	2.975E-03	3.450E-03
12															5.905E-03	4.770E-03		3.728E-03	3.311E-03	3.019E-03	3.476E-03
13															5.947E-03	4.798E-03		3.818E-03	3.394E-03	3.049E-03	3.536E-03
14															5.900E-03	4.892E-03		3.803E-03	3.484E-03	3.138E-03	3.628E-03
15															5.789E-03	4.868E-03		3.840E-03	3.474E-03	3.091E-03	3.569E-03
16															5.668E-03	4.834E-03		3.778E-03	3.438E-03	3.136E-03	3.542E-03
17															5.447E-03	4.733E-03		3.804E-03	3.385E-03	3.070E-03	3.432E-03
18															5.324E-03	4.674E-03		3.682E-03	3.325E-03	3.076E-03	3.370E-03
19															4.894E-03	4.314E-03		3.495E-03	3.204E-03	2.839E-03	3.227E-03

Greatest Total Number of Reactions by Source Energy for All Models

Table 8. Greatest Total Number of Reactions-cm^2 by Source Energy for All Models

Source Energy (MeV)	1.00E-8	1.00E-4	1	4	8	10	14	16	18	20
Pyramid Model # of RXNs-cm2	11.6272	15.8592	0.6956	0.3765	0.2405	0.1979	0.1553	0.1405	0.1255	0.1437
Concave Model # of RXNs-cm2	6.5151	14.6600	0.6698	0.3709	0.2385	0.1976	0.1546	0.1398	0.1264	0.1426
Wedge Model # of RXNs-cm2	6.9070	12.7181	0.6781	0.3730	0.2381	0.1970	0.1540	0.1387	0.1261	0.1440
Opposite Model # of RXNs-cm2	7.0772	12.7923	0.6725	0.3687	0.2379	0.1957	0.1536	0.1394	0.1255	0.1451
Largest Value	11.6272	15.8592	0.6956	0.3765	0.2405	0.1979	0.1553	0.1405	0.1264	0.1451

APPENDIX B

5X25 DETECTOR ARRAYS TOTAL NUMBER OF REACTIONS BY SOURCE ENERGY

5x25 Detector Array Total Number of Reactions-cm^2 by Source Energy

Table 9. 5x25 Detector Array Total Number of Reactions-cm^2 by Source Energy

Source Energy (MeV)	Total # of Reactions-cm^2	# of Reactions-cm^2 by Panel				
		p24	p2	p7	p13	p15
1.00E-08	22.1421	12.0503	7.1546	2.0807	0.5831	0.2734
1.00E-07	33.7336	15.6133	12.8720	3.6955	1.0461	0.5067
1.00E-06	40.8006	17.2808	16.3252	5.0571	1.4336	0.7040
1.00E-05	43.0140	17.3333	17.3120	5.8425	1.6956	0.8307
1.00E-04	39.5666	13.8794	16.5274	6.3483	1.8840	0.9275
1.00E-03	33.3224	9.0945	14.4153	6.7031	2.0730	1.0365
1.00E-02	29.6633	6.0875	12.4622	7.4228	2.4464	1.2444
1.00E-01	29.8121	4.3644	10.3932	9.3798	3.6906	1.9840
1.00E+00	24.9107	1.4942	4.1046	8.1257	6.5216	4.6646
2.00E+00	22.6605	1.0665	2.7407	6.5774	6.8438	5.4322
3.00E+00	18.8577	0.7438	1.9172	5.0872	6.0545	5.0550
4.00E+00	15.1445	0.5456	1.4304	3.9798	4.9860	4.2028
5.00E+00	14.1550	0.4731	1.2332	3.5551	4.7490	4.1446
6.00E+00	12.3665	0.4099	1.0311	3.0304	4.2014	3.6937
7.00E+00	10.8038	0.3322	0.8401	2.5743	3.7262	3.3309
8.00E+00	9.4182	0.2667	0.7119	2.2504	3.2775	2.9117
9.00E+00	8.2328	0.2219	0.5991	1.9346	2.8838	2.5933
1.00E+01	7.4742	0.1964	0.5248	1.7204	2.6345	2.3980
1.10E+01	7.1673	0.1894	0.5093	1.6543	2.5233	2.2909
1.20E+01	6.5916	0.1788	0.4719	1.5242	2.3130	2.1038
1.30E+01	6.0123	0.1640	0.4276	1.3756	2.1200	1.9251
1.40E+01	5.7912	0.1616	0.4152	1.3282	2.0320	1.8542
1.50E+01	5.5611	0.1570	0.4002	1.2702	1.9544	1.7792
1.60E+01	5.2762	0.1510	0.3789	1.2003	1.8505	1.6955
1.70E+01	4.9335	0.1437	0.3553	1.1156	1.7306	1.5884
1.80E+01	4.7636	0.1393	0.3436	1.0776	1.6697	1.5334
1.90E+01	4.5419	0.1345	0.3264	1.0271	1.5908	1.4631
2.00E+01	5.4609	0.1617	0.4208	1.2993	1.8722	1.7069

5x25 Detector Array with Moderator and Detector Separation Total Number of Reactions-cm^2 by Source Energy

Table 10. 5x25 Detector Array with Moderator and Detector Separation Total Number of Reactions-cm^2 by Source Energy

Source Energy (MeV)	Total # of Reactions-cm^2	# of Reactions-cm^2 by Panel				
		p24	p2	p7	p13	p15
1.00E-08	11.2391	9.1378	1.0934	0.6693	0.2481	0.0906
1.00E-07	14.7528	10.8797	2.0736	1.1959	0.4400	0.1637
1.00E-06	16.8501	11.6128	2.7957	1.6231	0.5957	0.2230
1.00E-05	17.3336	11.4436	3.0991	1.8392	0.6943	0.2574
1.00E-04	14.4868	8.4507	3.0700	1.9219	0.7574	0.2868
1.00E-03	10.4850	4.6566	2.7945	1.9202	0.8058	0.3079
1.00E-02	8.4664	2.6464	2.5798	1.9770	0.9038	0.3595
1.00E-01	8.4003	1.9352	2.4438	2.2525	1.2290	0.5398
1.00E+00	6.9647	0.8100	1.3731	1.9455	1.7438	1.0924
2.00E+00	6.4687	0.6775	1.0900	1.6847	1.7725	1.2439
3.00E+00	5.3986	0.4968	0.8322	1.3654	1.5534	1.1509
4.00E+00	4.3140	0.3730	0.6398	1.0799	1.2640	0.9573
5.00E+00	4.0443	0.3293	0.5702	0.9894	1.2149	0.9406
6.00E+00	3.5784	0.2955	0.4985	0.8609	1.0759	0.8476
7.00E+00	3.1217	0.2423	0.4155	0.7444	0.9550	0.7646
8.00E+00	2.6670	0.1920	0.3459	0.6385	0.8298	0.6608
9.00E+00	2.3305	0.1614	0.2999	0.5508	0.7336	0.5848
1.00E+01	2.1213	0.1450	0.2675	0.4982	0.6684	0.5423
1.10E+01	2.0291	0.1387	0.2543	0.4785	0.6396	0.5179
1.20E+01	1.8820	0.1330	0.2388	0.4420	0.5895	0.4787
1.30E+01	1.7297	0.1240	0.2185	0.4052	0.5410	0.4410
1.40E+01	1.6714	0.1211	0.2138	0.3910	0.5240	0.4215
1.50E+01	1.6127	0.1183	0.2090	0.3771	0.5004	0.4078
1.60E+01	1.5376	0.1157	0.1987	0.3575	0.4763	0.3895
1.70E+01	1.4460	0.1111	0.1866	0.3351	0.4482	0.3649
1.80E+01	1.4042	0.1080	0.1817	0.3238	0.4337	0.3570
1.90E+01	1.3448	0.1048	0.1741	0.3116	0.4156	0.3388
2.00E+01	1.6112	0.1208	0.2169	0.3840	0.4925	0.3969

5x25 Detector Array with 2.54 cm Polyethylene Layer Behind the Detector Array Total Number of Reactions-cm^2 by Source Energy

Table 11. 5x25 Detector Array with 2.54 cm Polyethylene Layer Behind the Detector Array Total Number of Reactions-cm^2 by Source Energy

Source Energy (MeV)	Total # of Reactions-cm^2	# of Reactions-cm^2 by Panel				
		p24	p2	p7	p13	p15
1.00E-08	32.7203	19.5606	9.2967	2.7378	0.7697	0.3556
1.00E-07	46.9288	23.4105	16.6001	4.8810	1.3807	0.6564
1.00E-06	55.6571	24.9621	21.2114	6.6776	1.8906	0.9155
1.00E-05	58.8742	25.0795	22.7380	7.7395	2.2354	1.0817
1.00E-04	56.6800	22.1471	22.4029	8.4378	2.4858	1.2064
1.00E-03	51.8166	17.7824	20.9358	9.0146	2.7386	1.3453
1.00E-02	50.1459	14.9755	20.1106	10.1910	3.2509	1.6179
1.00E-01	54.3967	12.7957	20.3706	13.6546	4.9821	2.5937
1.00E+00	50.7633	5.9995	12.1109	15.2607	10.3605	7.0318
2.00E+00	48.0963	4.2324	9.0225	13.7671	12.0197	9.0545
3.00E+00	41.2754	3.0211	6.7038	11.3302	11.2780	8.9423
4.00E+00	33.8679	2.3146	5.2264	9.1749	9.5335	7.6184
5.00E+00	32.1115	1.9680	4.5240	8.4060	9.4184	7.7950
6.00E+00	28.3235	1.6658	3.8329	7.2985	8.4594	7.0669
7.00E+00	25.1164	1.3599	3.1935	6.3435	7.6847	6.5347
8.00E+00	22.1870	1.1890	2.8218	5.6239	6.8144	5.7380
9.00E+00	19.5388	0.9947	2.4033	4.8765	6.0803	5.1839
1.00E+01	17.8306	0.8652	2.0997	4.3781	5.6248	4.8627
1.10E+01	17.1822	0.8462	2.0425	4.2295	5.4062	4.6578
1.20E+01	15.8105	0.7856	1.8810	3.8927	4.9660	4.2853
1.30E+01	14.5047	0.7075	1.7008	3.5463	4.5856	3.9645
1.40E+01	13.9731	0.6835	1.6448	3.4184	4.4111	3.8152
1.50E+01	13.4466	0.6581	1.5801	3.2778	4.2490	3.6816
1.60E+01	12.7556	0.6261	1.4850	3.1028	4.0372	3.5046
1.70E+01	11.9427	0.5814	1.3871	2.8932	3.7842	3.2969
1.80E+01	11.5132	0.5632	1.3428	2.7827	3.6469	3.1776
1.90E+01	11.0082	0.5377	1.2731	2.6615	3.4907	3.0452
2.00E+01	50.7633	5.9995	12.1109	15.2607	10.3605	7.0318

APPENDIX C

5X30 DETECTOR ARRAYS DATA

Table 12. Total Number of Reactions-cm^2 by Source Energy for 5x25 and 5x30 Detector Array Models

Source Energy (MeV)	5x25 Detector Array	5x30 Detector Array with 7.625 cm moderator	5x30 Detector Array with 12.705 cm moderator	Difference of Total # of Reactions-cm^2 between 5x25 and 5x30 (7.625 cm moderator)	Difference of Total # of Reactions-cm^2 between 5x25 and 5x30 (12.705 cm moderator)
	Total # of Reactions-cm^2				
1.00E-08	22.1421	22.2171	22.1800	0.0751	0.0380
1.00E-07	33.7336	33.8475	33.7882	0.1139	0.0546
1.00E-06	40.8006	40.9538	40.8769	0.1532	0.0763
1.00E-05	43.0140	43.1800	43.0949	0.1660	0.0809
1.00E-04	39.5666	39.7397	39.6467	0.1731	0.0802
1.00E-03	33.3224	33.5326	33.4310	0.2102	0.1086
1.00E-02	29.6633	29.9173	29.8004	0.2541	0.1371
1.00E-01	29.8121	30.2476	30.1772	0.4355	0.3651
1.00E+00	24.9107	27.0278	28.8219	2.1171	3.9111
2.00E+00	22.6605	25.8413	27.2287	3.1807	4.5682
3.00E+00	18.8577	21.8256	22.5343	2.9679	3.6765
4.00E+00	15.1445	18.0508	18.5625	2.9063	3.4180
5.00E+00	14.1550	17.5402	17.7589	3.3852	3.6040
6.00E+00	12.3665	15.5838	15.6539	3.2173	3.2875
7.00E+00	10.8038	13.9192	13.8010	3.1154	2.9972
8.00E+00	9.4182	12.1927	12.0738	2.7745	2.6555
9.00E+00	8.2328	10.7919	10.5874	2.5591	2.3546
1.00E+01	7.4742	9.8509	9.5994	2.3767	2.1252
1.10E+01	7.1673	9.4538	9.1948	2.2866	2.0276
1.20E+01	6.5916	8.7060	8.4647	2.1144	1.8731
1.30E+01	6.0123	7.9784	7.7420	1.9661	1.7297

1.40E+01	5.7912	7.6780	7.4385	1.8868	1.6473
1.50E+01	5.5611	7.3870	7.1524	1.8259	1.5913
1.60E+01	5.2762	7.0196	6.7775	1.7434	1.5013
1.70E+01	4.9335	6.5694	6.3378	1.6359	1.4042
1.80E+01	4.7636	7.0776	6.9070	2.3140	2.1434
1.90E+01	4.5419	6.0576	5.8355	1.5157	1.2936
2.00E+01	5.4609	7.0776	6.9070	1.6167	1.4461

APPENDIX D

5X25 DETECTOR ARRAY MODERATED AND UNMODERATED SOURCE DATA

Table 13. Number of Reactions-cm^2 for the 5x25 Detector Array with Moderated and Unmoderated Sources

Source Energy	Total # of Reactions-cm^2	# of Reactions-cm^2 by Model				
		p24	p2	p7	p13	p15
Pu Source	2.3722E+01	1.7392E+00	4.2075E+00	7.3482E+00	6.0001E+00	4.4269E+00
Watt Fission Spectrum	2.3138E+01	1.5536E+00	3.8396E+00	7.0983E+00	6.0795E+00	4.5670E+00
AmBe Source	1.7183E+01	9.4851E-01	2.3283E+00	4.8471E+00	5.0075E+00	4.0515E+00
AmB Source	1.9645E+01	8.8695E-01	2.2752E+00	5.5548E+00	6.0346E+00	4.8936E+00
Cf-252 Source in 12in poly sphere	2.8206E+01	8.2763E+00	8.7275E+00	5.5781E+00	3.3249E+00	2.2988E+00
Cf-252 Source in 150mm D2O sphere	3.1592E+01	7.7850E+00	1.1612E+01	7.0696E+00	3.1721E+00	1.9535E+00
Cf-252 Source in 60cm iron sphere	2.9513E+01	3.5656E+00	7.8342E+00	9.5348E+00	5.2677E+00	3.3112E+00

APPENDIX E

LEAST SQUARES FIT DATA FOR 5X25 DETECTOR ARRAY

Table 14. M Matrix

M11	M12	M13	M14	M15
3.36E+01	8.05E+01	1.09E+02	8.57E+01	6.46E+01
M21	M22	M23	M24	M25
8.18E+01	1.95E+02	2.71E+02	2.16E+02	1.63E+02
M31	M32	M33	M34	M35
1.09E+02	2.74E+02	5.01E+02	4.91E+02	3.93E+02
M41	M42	M43	M44	M45
8.48E+01	2.18E+02	4.83E+02	7.70E+02	4.44E+02
M51	M52	M53	M54	M55
6.46E+01	1.67E+02	3.93E+02	4.53E+02	3.79E+02

Table 15. Inverse M Matrix

-2.133324179	1.079165225	-0.219544405	-0.000167526	0.127818715
1.307209302	-0.588713895	0.055446078	0.000680961	-0.028207123
-0.452245943	0.150543882	0.049637947	-0.001609849	-0.037133501
0.003329093	-0.000824348	-0.001659762	0.00427449	-0.003496367
0.252921364	-0.079834866	-0.036441648	-0.003713472	0.035929221

Table 16. b Matrix

1.94E+01
4.92E+01
1.11E+02
1.32E+02
1.13E+02

Table 17. a Matrix

1.689480471
-0.551315119
-0.22267707
0.011368353
0.468935522

Table 18. Response Function Values for Different Source Energies

Source Energy (MeV)	Response, $R(E_i)$
1.00E-08	1.61E+01
1.00E-07	1.87E+01
1.00E-06	1.94E+01
1.00E-05	1.88E+01
1.00E-04	1.34E+01
1.00E-03	6.43E+00
1.00E-02	2.37E+00
1.00E-01	5.27E-01
1.00E+00	7.14E-01
2.00E+00	1.45E+00
3.00E+00	1.51E+00
4.00E+00	1.27E+00
5.00E+00	1.33E+00
6.00E+00	1.23E+00
7.00E+00	1.13E+00
8.00E+00	9.60E-01
9.00E+00	8.63E-01
1.00E+01	8.14E-01
1.10E+01	7.74E-01
1.20E+01	7.15E-01
1.30E+01	6.62E-01
1.40E+01	6.41E-01
1.50E+01	6.18E-01
1.60E+01	5.95E-01
1.70E+01	5.63E-01
1.80E+01	5.44E-01
1.90E+01	5.23E-01
2.00E+01	5.74E-01

Table 19. M Matrix from Additional Energies

M11	M12	M13	M14	M15
3.36E+01	8.05E+01	1.09E+02	8.57E+01	6.46E+01
M21	M22	M23	M24	M25
8.18E+01	1.95E+02	2.71E+02	2.16E+02	1.63E+02
M31	M32	M33	M34	M35
1.09E+02	2.74E+02	5.01E+02	4.91E+02	3.93E+02
M41	M42	M43	M44	M45
8.48E+01	2.18E+02	4.83E+02	7.70E+02	4.44E+02
M51	M52	M53	M54	M55
6.46E+01	1.67E+02	3.93E+02	4.53E+02	3.79E+02

Table 20. Inverse M Matrix from Additional Energies

-2.133324179	1.079165225	-0.219544405	-0.000167526	0.127818715
1.307209302	-0.588713895	0.055446078	0.000680961	-0.028207123
-0.452245943	0.150543882	0.049637947	-0.001609849	-0.037133501
0.003329093	-0.000824348	-0.001659762	0.00427449	-0.003496367
0.252921364	-0.079834866	-0.036441648	-0.003713472	0.035929221

Table 21. b Matrix from Additional Energies

1.94E+01
4.92E+01
1.11E+02
1.32E+02
1.13E+02

Table 22. a Matrix from Additional Energies

1.689480471
-0.551315119
-0.22267707
0.011368353
0.468935522

Table 23. Response Function Values for Different Source Energies from Additional Energies

Source Energy (MeV)	Response, R(E_i)	Source Energy (MeV)	Response, R(E_i)	Source Energy (MeV)	Response, R(E_i)
1.00E-08	8.67E-01	3.00E-04	4.91E-01	3.00E+00	1.56E+00
2.00E-08	9.13E-01	4.00E-04	4.50E-01	3.50E+00	1.30E+00
3.00E-08	9.28E-01	5.00E-04	4.20E-01	4.00E+00	1.30E+00
4.00E-08	9.35E-01	6.00E-04	3.97E-01	4.50E+00	1.31E+00
5.00E-08	9.42E-01	7.00E-04	3.78E-01	5.00E+00	1.28E+00
6.00E-08	9.46E-01	8.00E-04	3.63E-01	5.50E+00	1.20E+00
7.00E-08	9.46E-01	9.00E-04	3.49E-01	6.00E+00	1.14E+00
8.00E-08	9.50E-01	1.00E-03	3.39E-01	6.50E+00	1.10E+00
9.00E-08	9.51E-01	2.00E-03	2.75E-01	7.00E+00	1.03E+00
1.00E-07	9.52E-01	3.00E-03	2.48E-01	7.50E+00	9.48E-01
2.00E-07	9.58E-01	4.00E-03	2.33E-01	8.00E+00	8.99E-01
3.00E-07	9.61E-01	5.00E-03	2.26E-01	8.50E+00	8.62E-01
4.00E-07	9.63E-01	6.00E-03	2.17E-01	9.00E+00	7.99E-01
5.00E-07	9.64E-01	7.00E-03	2.15E-01	9.50E+00	7.61E-01
6.00E-07	9.65E-01	8.00E-03	2.13E-01	1.00E+01	7.38E-01
7.00E-07	9.64E-01	9.00E-03	2.11E-01	1.05E+01	7.15E-01
8.00E-07	9.64E-01	1.00E-02	2.10E-01	1.10E+01	7.05E-01
9.00E-07	9.66E-01	2.00E-02	2.07E-01	1.15E+01	6.70E-01
1.00E-06	9.66E-01	3.00E-02	2.31E-01	1.20E+01	6.47E-01
2.00E-06	9.73E-01	4.00E-02	2.51E-01	1.25E+01	6.18E-01
3.00E-06	9.71E-01	5.00E-02	2.79E-01	1.30E+01	5.94E-01
4.00E-06	9.72E-01	6.00E-02	2.93E-01	1.35E+01	5.83E-01
5.00E-06	9.70E-01	7.00E-02	3.14E-01	1.40E+01	5.71E-01
6.00E-06	9.68E-01	8.00E-02	3.36E-01	1.45E+01	5.53E-01
7.00E-06	9.62E-01	9.00E-02	3.63E-01	1.50E+01	5.48E-01
8.00E-06	9.58E-01	1.00E-01	3.91E-01	1.55E+01	5.32E-01
9.00E-06	9.54E-01	2.00E-01	6.95E-01	1.60E+01	5.22E-01
1.00E-05	9.47E-01	3.00E-01	8.79E-01	1.65E+01	5.07E-01
2.00E-05	8.98E-01	4.00E-01	9.38E-01	1.70E+01	4.89E-01
3.00E-05	8.56E-01	5.00E-01	1.08E+00	1.75E+01	4.81E-01
4.00E-05	8.17E-01	6.00E-01	1.23E+00	1.80E+01	4.72E-01
5.00E-05	7.83E-01	7.00E-01	1.29E+00	1.85E+01	4.61E-01
6.00E-05	7.55E-01	8.00E-01	1.39E+00	1.90E+01	4.50E-01
7.00E-05	7.30E-01	9.00E-01	1.47E+00	1.95E+01	4.43E-01
8.00E-05	7.08E-01	1.00E+00	1.38E+00	2.00E+01	5.22E-01
9.00E-05	6.86E-01	1.50E+00	1.62E+00		
1.00E-04	6.69E-01	2.00E+00	1.66E+00		
2.00E-04	5.55E-01	2.50E+00	1.61E+00		

Table 24. Response Function Values for the 1E-8 to 1E-5 MeV Energy Range for Different Source Energies

Source Energy (MeV)	Response, $R(E_i)$	Source Energy (MeV)	Response, $R(E_i)$
1.00E-08	8.97E-01	6.00E-07	9.97E-01
2.00E-08	9.51E-01	7.00E-07	9.93E-01
3.00E-08	9.67E-01	8.00E-07	9.93E-01
4.00E-08	9.75E-01	9.00E-07	9.98E-01
5.00E-08	9.81E-01	1.00E-06	9.95E-01
6.00E-08	9.87E-01	2.00E-06	1.01E+00
7.00E-08	9.86E-01	3.00E-06	1.00E+00
8.00E-08	9.90E-01	4.00E-06	1.01E+00
9.00E-08	9.91E-01	5.00E-06	1.00E+00
1.00E-07	9.92E-01	6.00E-06	1.01E+00
2.00E-07	9.95E-01	7.00E-06	9.97E-01
3.00E-07	9.97E-01	8.00E-06	9.92E-01
4.00E-07	9.95E-01	9.00E-06	9.93E-01
5.00E-07	9.97E-01	1.00E-05	9.86E-01

Table 25. Response Function Values for the 1E-4 to 1E-1 MeV Energy Range for Different Source Energies

Source Energy (MeV)	Response, $R(E_i)$	Source Energy (MeV)	Response, $R(E_i)$
1.00E-04	1.31E+00	6.00E-03	1.10E+00
2.00E-04	1.26E+00	7.00E-03	1.10E+00
3.00E-04	1.23E+00	8.00E-03	1.10E+00
4.00E-04	1.21E+00	9.00E-03	1.11E+00
5.00E-04	1.20E+00	1.00E-02	1.11E+00
6.00E-04	1.18E+00	2.00E-02	1.09E+00
7.00E-04	1.17E+00	3.00E-02	1.16E+00
8.00E-04	1.17E+00	4.00E-02	1.19E+00
9.00E-04	1.16E+00	5.00E-02	1.22E+00
1.00E-03	1.15E+00	6.00E-02	1.23E+00
2.00E-03	1.12E+00	7.00E-02	1.25E+00
3.00E-03	1.11E+00	8.00E-02	1.27E+00
4.00E-03	1.10E+00	9.00E-02	1.29E+00
5.00E-03	1.10E+00	1.00E-01	1.31E+00

Table 26. Response Function Values for the 1 to 4 MeV Energy Range for Different Source Energies

Source Energy (MeV)	Response, $R(E_i)$
1.00E+00	9.77E-01
1.50E+00	1.02E+00
2.00E+00	1.02E+00
2.50E+00	9.61E-01
3.00E+00	1.02E+00
3.50E+00	9.56E-01
4.00E+00	1.04E+00

Table 27. Response Function Values for the 6 to 12 MeV Energy Range for Different Source Energies

Source Energy (MeV)	Response, $R(E_i)$	Source Energy (MeV)	Response, $R(E_i)$
6.00E+00	9.77E-01	9.50E+00	9.75E-01
6.50E+00	1.02E+00	1.00E+01	1.00E+00
7.00E+00	1.01E+00	1.05E+01	1.00E+00
7.50E+00	9.80E-01	1.10E+01	1.02E+00
8.00E+00	9.84E-01	1.15E+01	9.61E-01
8.50E+00	1.11E+00	1.20E+01	8.54E-01
9.00E+00	9.92E-01		

Table 28. Response Function Values for the 14 to 20 MeV Energy Range for Different Source Energies

Source Energy (MeV)	Response, $R(E_i)$	Source Energy (MeV)	Response, $R(E_i)$
1.40E+01	1.01E+00	1.75E+01	1.02E+00
1.45E+01	9.82E-01	1.80E+01	9.80E-01
1.50E+01	1.00E+00	1.85E+01	9.87E-01
1.55E+01	9.92E-01	1.90E+01	1.00E+00
1.60E+01	1.02E+00	1.95E+01	9.75E-01
1.65E+01	1.03E+00	2.00E+01	9.95E-01
1.70E+01	1.00E+00		

APPENDIX F

MCNP INPUT CODE EXAMPLES

5x5 Pyramid Model MCNP Input Code

```
Pyramid Li-6 Detector Array 5x5
c cells
    1      0           1 :-2 :3 :-4 :5 :-6  $void
    2      6 -0.001205 -7 8 -9 10 -11 12  fill=1 $detector region
    3      6 -0.001205 #1 #2  $source region
    4      6 -0.001205 -15 16 -17 18  u=1 lat=1 $ROW 1 lattice definition
             fill=-2:2 -2:2 0:0
      14  14  14  14  14  $ROW 1
      14  15  15  15  14  $ROW 2
      14  15  16  15  14  $ROW 3
      14  15  15  15  14  $ROW 4
      14  14  14  14  14  $ROW 5
c ----------------------------------------------------
c Universe Key
c    Universe 1- Lattice Box
c    Universe 2- 2.545   cm moderator
c    Universe 3- 3.18    cm moderator
c    Universe 4- 3.815   cm moderator
c    Universe 5- 4.45    cm moderator
c    Universe 6- 5.085   cm moderator
c    Universe 7- 5.72    cm moderator
c    Universe 8- 6.355   cm moderator
c    Universe 9- 6.99    cm moderator
c    Universe 10- 7.625  cm moderator
c    Universe 11- 8.26   cm moderator
c    Universe 12- 8.895  cm moderator
c    Universe 13- 9.53   cm moderator
c    Universe 14- 10.165 cm moderator
c    Universe 15- 10.8   cm moderator
c    Universe 16- 11.435 cm moderator
c    Universe 17- 12.07  cm moderator
c    Universe 18- 12.705 cm moderator
c    Universe 19- 13.34  cm moderator
c    Universe 20- 13.975 cm moderator
c    Universe 21- 14.61  cm moderator
c    Universe 22- 15.245 cm moderator
```

```
c    Universe 23- 22.865 cm moderator
c    Universe 24- 0      cm moderator
c ----------------------------------------------------
c Moderators
c 2.545 cm moderator
    5   408  -2.635 -19  u=2 $detector
    6   256  -0.9300 -20 19  u=2 $moderator
    7     6 -0.001205 20  u=2 $air above moderator
c 3.18 cm moderator
    8   408  -2.635 -19  u=3 $detector
    9   256  -0.9300 -21 19  u=3 $moderator
   10     6 -0.001205 21  u=3 $air above moderator
c 3.815 cm moderator
   11   408  -2.635 -19  u=4 $detector
   12   256  -0.9300 -22 19  u=4 $moderator
   13     6 -0.001205 22  u=4 $air above moderator
c 4.45 cm moderator
   14   408  -2.635 -19  u=5 $detector
   15   256  -0.9300 -23 19  u=5 $moderator
   16     6 -0.001205 23  u=5 $air above moderator
c 5.085 cm moderator
   17   408  -2.635 -19  u=6 $detector
   18   256  -0.9300 -24 19  u=6 $moderator
   19     6 -0.001205 24  u=6 $air above moderator
c 5.72 cm moderator
   20   408  -2.635 -19  u=7 $detector
   21   256  -0.9300 -25 19  u=7 $moderator
   22     6 -0.001205 25  u=7 $air above moderator
c 6.355 cm moderator
   23   408  -2.635 -19  u=8 $detector
   24   256  -0.9300 -26 19  u=8 $moderator
   25     6 -0.001205 26  u=8 $air above moderator
c 6.99 cm moderator
   26   408  -2.635 -19  u=9 $detector
   27   256  -0.9300 -27 19  u=9 $moderator
   28     6 -0.001205 27  u=9 $air above moderator
c 7.625 cm moderator
   29   408  -2.635 -19  u=10 $detector
   30   256  -0.9300 -28 19  u=10 $moderator
   31     6 -0.001205 28  u=10 $air above moderator
c 8.26 cm moderator
   32   408  -2.635 -19  u=11 $detector
   33   256  -0.9300 -29 19  u=11 $moderator
```

```
   34     6 -0.001205 29  u=11 $air above moderator
c 8.895 cm moderator
   35   408  -2.635 -19  u=12 $detector
   36   256  -0.9300 -30 19  u=12 $moderator
   37     6 -0.001205 30  u=12 $air above moderator
c 9.53 cm moderator
   38   408  -2.635 -19  u=13 $detector
   39   256  -0.9300 -31 19  u=13 $moderator
   40     6 -0.001205 31  u=13 $air above moderator
c 10.165 cm moderator
   41   408  -2.635 -19  u=14 $detector
   42   256  -0.9300 -32 19  u=14 $moderator
   43     6 -0.001205 32  u=14 $air above moderator
c 10.8 cm moderator
   44   408  -2.635 -19  u=15 $detector
   45   256  -0.9300 -33 19  u=15 $moderator
   46     6 -0.001205 33  u=15 $air above moderator
c 11.435 cm moderator
   47   408  -2.635 -19  u=16 $detector
   48   256  -0.9300 -34 19  u=16 $moderator
   49     6 -0.001205 34  u=16 $air above moderator
c 12.07 cm moderator
   50   408  -2.635 -19  u=17 $detector
   51   256  -0.9300 -35 19  u=17 $moderator
   52     6 -0.001205 35  u=17 $air above moderator
c 12.705 cm moderator
   53   408  -2.635 -19  u=18 $detector
   54   256  -0.9300 -36 19  u=18 $moderator
   55     6 -0.001205 36  u=18 $air above moderator
c 13.34 cm moderator
   56   408  -2.635 -19  u=19 $detector
   57   256  -0.9300 -37 19  u=19 $moderator
   58     6 -0.001205 37  u=19 $air above moderator
c 13.975 cm moderator
   59   408  -2.635 -19  u=20 $detector
   60   256  -0.9300 -38 19  u=20 $moderator
   61     6 -0.001205 38  u=20 $air above moderator
c 14.61 cm moderator
   62   408  -2.635 -19  u=21 $detector
   63   256  -0.9300 -39 19  u=21 $moderator
   64     6 -0.001205 39  u=21 $air above moderator
c 15.245 cm moderator
   65   408  -2.635 -19  u=22 $detector
```

```
   66   256  -0.9300 -40 19  u=22 $moderator
   67     6 -0.001205 40  u=22 $air above moderator
c 22.865 cm moderator
   68   408  -2.635 -19  u=23 $detector
   69   256  -0.9300 -41 19  u=23 $moderator
   70     6 -0.001205 41  u=23 $air above moderator
c 0 cm moderator
   71   408  -2.635 -19  u=24 $detector
   72     6 -0.001205 19  u=24 $air above detector

c surfaces
c 1-6 Box defining void region
    1        pz 1030
    2        pz -26
    3        px 100
    4        px -100
    5        py 100
    6        py -100
c 7-12 Lattice Box
    7        pz 25
    8        pz -25
    9        px 10
   10        px -10
   11        py 10
   12        py -10
c   13        pz 25
c   14        pz -25
c 15-18 Lattice Cells
   15        px 2
   16        px -2
   17        py 2
   18        py -2
   19       rcc 0 0 -25 0 0 1 1  $detector
c 20-41 Moderators
   20       rpp -2 2 -2 2 -25 -22.455
   21       rpp -2 2 -2 2 -25 -21.82
   22       rpp -2 2 -2 2 -25 -21.185
   23       rpp -2 2 -2 2 -25 -20.55
   24       rpp -2 2 -2 2 -25 -19.915
   25       rpp -2 2 -2 2 -25 -19.28
   26       rpp -2 2 -2 2 -25 -18.645
   27       rpp -2 2 -2 2 -25 -18.01
   28       rpp -2 2 -2 2 -25 -17.375
```

```
   29       rpp -2 2 -2 2 -25 -16.74
   30       rpp -2 2 -2 2 -25 -16.105
   31       rpp -2 2 -2 2 -25 -15.47
   32       rpp -2 2 -2 2 -25 -14.835
   33       rpp -2 2 -2 2 -25 -14.2
   34       rpp -2 2 -2 2 -25 -13.565
   35       rpp -2 2 -2 2 -25 -12.93
   36       rpp -2 2 -2 2 -25 -12.295
   37       rpp -2 2 -2 2 -25 -11.66
   38       rpp -2 2 -2 2 -25 -11.025
   39       rpp -2 2 -2 2 -25 -10.39
   40       rpp -2 2 -2 2 -25 -9.755
   41       rpp -2 2 -2 2 -25 -2.135

mode n
c ---------------
c Materials
c ---------------
c     -- Mat  408 Lithium Fluoride --
c         density: 2.635E+00 g/cc
m408  3006.80c    -0.267585
      9019.80c    -0.732415
c     -- Mat  256  Polyethylene --
c         density: 9.300E-01 g/cc
m256  1001.80c    -0.143711
      6000.80c    -0.856289
c     -- Mat   6  Air-Dry --
c         density: 1.205E-03 g/cc
m6    6000.80c    -1.24e-04     7014.80c    -7.55268e-01
      8016.80c    -2.31781e-01  18036.80c   -1.2827e-02
imp:n  0            1 70r         $ 1, 72
c ------------------------------------------------------
c Source Description
c ------------------------------------------------------
sdef pos 0 0 45 x=d1 y=d2 z=1025 par=1 erg=1e-4 vec=0 0 -1 dir=1
si1 -10 10 $ sampling range Xmin to Xmax
sp1  0  1  $ weighting for x sampling
si2 -10 10 $ sampling range Ymin to Ymax
sp2  0  1  $ weighting for y sampling
c sp3 -3
c
c      --------------------------------
c      Tally definitions
```

```
c      --------------------------------
fc24 Triton Production Rate in detector cells
f24:n (41<4[-2:2 -2:2 0:0]<2)
     (44<4[-2:2 -2:2 0:0]<2)
     (47<4[-2:2 -2:2 0:0]<2)
fm24 -1 408 105
nps 10e6
print
prdmp 0 0 1 0 0
```

5x5 Concave Model MCNP Input Code

```
Concave Detector Array 5x5
c cells
    1     0            1 :-2 :3 :-4 :5 :-6  $void
    2     6 -0.001205  -7 8 -9 10 -11 12  fill=1 $detector region
    3     6 -0.001205  #1 #2  $source region
    4     6 -0.001205 -15 16 -17 18  u=1 lat=1 $ROW 1 lattice definition
            fill=-2:2 -2:2 0:0
      5 5  5  5 5  $ROW 1
      5 4  4  4 5  $ROW 2
      5 4  3  4 5  $ROW 3
      5 4  4  4 5  $ROW 4
      5 5  5  5 5  $ROW 5
c ----------------------------------------------------
c Universe Key
c    Universe 1- Lattice Box
c    Universe 2- 2.545   cm moderator
c    Universe 3- 3.18    cm moderator
c    Universe 4- 3.815   cm moderator
c    Universe 5- 4.45    cm moderator
c    Universe 6- 5.085   cm moderator
c    Universe 7- 5.72    cm moderator
c    Universe 8- 6.355   cm moderator
c    Universe 9- 6.99    cm moderator
c    Universe 10- 7.625  cm moderator
c    Universe 11- 8.26   cm moderator
c    Universe 12- 8.895  cm moderator
c    Universe 13- 9.53   cm moderator
c    Universe 14- 10.165 cm moderator
c    Universe 15- 10.8   cm moderator
c    Universe 16- 11.435 cm moderator
c    Universe 17- 12.07  cm moderator
c    Universe 18- 12.705 cm moderator
```

```
c    Universe 19- 13.34  cm moderator
c    Universe 20- 13.975 cm moderator
c    Universe 21- 14.61  cm moderator
c    Universe 22- 15.245 cm moderator
c    Universe 23- 22.865 cm moderator
c    Universe 24- 0      cm moderator
c ----------------------------------------------------
c Moderators
c 2.545 cm moderator
    5   408  -2.635 -19  u=2 $detector
    6   256  -0.9300 -20 19  u=2 $moderator
    7      6 -0.001205 20  u=2 $air above moderator
c 3.18 cm moderator
    8   408  -2.635 -19  u=3 $detector
    9   256  -0.9300 -21 19  u=3 $moderator
   10      6 -0.001205 21  u=3 $air above moderator
c 3.815 cm moderator
   11   408  -2.635 -19  u=4 $detector
   12   256  -0.9300 -22 19  u=4 $moderator
   13      6 -0.001205 22  u=4 $air above moderator
c 4.45 cm moderator
   14   408  -2.635 -19  u=5 $detector
   15   256  -0.9300 -23 19  u=5 $moderator
   16      6 -0.001205 23  u=5 $air above moderator
c 5.085 cm moderator
   17   408  -2.635 -19  u=6 $detector
   18   256  -0.9300 -24 19  u=6 $moderator
   19      6 -0.001205 24  u=6 $air above moderator
c 5.72 cm moderator
   20   408  -2.635 -19  u=7 $detector
   21   256  -0.9300 -25 19  u=7 $moderator
   22      6 -0.001205 25  u=7 $air above moderator
c 6.355 cm moderator
   23   408  -2.635 -19  u=8 $detector
   24   256  -0.9300 -26 19  u=8 $moderator
   25      6 -0.001205 26  u=8 $air above moderator
c 6.99 cm moderator
   26   408  -2.635 -19  u=9 $detector
   27   256  -0.9300 -27 19  u=9 $moderator
   28      6 -0.001205 27  u=9 $air above moderator
c 7.625 cm moderator
   29   408  -2.635 -19  u=10 $detector
   30   256  -0.9300 -28 19  u=10 $moderator
```

```
   31     6 -0.001205 28  u=10 $air above moderator
c 8.26 cm moderator
   32   408  -2.635 -19  u=11 $detector
   33   256  -0.9300 -29 19  u=11 $moderator
   34     6 -0.001205 29  u=11 $air above moderator
c 8.895 cm moderator
   35   408  -2.635 -19  u=12 $detector
   36   256  -0.9300 -30 19  u=12 $moderator
   37     6 -0.001205 30  u=12 $air above moderator
c 9.53 cm moderator
   38   408  -2.635 -19  u=13 $detector
   39   256  -0.9300 -31 19  u=13 $moderator
   40     6 -0.001205 31  u=13 $air above moderator
c 10.165 cm moderator
   41   408  -2.635 -19  u=14 $detector
   42   256  -0.9300 -32 19  u=14 $moderator
   43     6 -0.001205 32  u=14 $air above moderator
c 10.8 cm moderator
   44   408  -2.635 -19  u=15 $detector
   45   256  -0.9300 -33 19  u=15 $moderator
   46     6 -0.001205 33  u=15 $air above moderator
c 11.435 cm moderator
   47   408  -2.635 -19  u=16 $detector
   48   256  -0.9300 -34 19  u=16 $moderator
   49     6 -0.001205 34  u=16 $air above moderator
c 12.07 cm moderator
   50   408  -2.635 -19  u=17 $detector
   51   256  -0.9300 -35 19  u=17 $moderator
   52     6 -0.001205 35  u=17 $air above moderator
c 12.705 cm moderator
   53   408  -2.635 -19  u=18 $detector
   54   256  -0.9300 -36 19  u=18 $moderator
   55     6 -0.001205 36  u=18 $air above moderator
c 13.34 cm moderator
   56   408  -2.635 -19  u=19 $detector
   57   256  -0.9300 -37 19  u=19 $moderator
   58     6 -0.001205 37  u=19 $air above moderator
c 13.975 cm moderator
   59   408  -2.635 -19  u=20 $detector
   60   256  -0.9300 -38 19  u=20 $moderator
   61     6 -0.001205 38  u=20 $air above moderator
c 14.61 cm moderator
   62   408  -2.635 -19  u=21 $detector
```

```
   63   256  -0.9300 -39 19  u=21 $moderator
   64     6 -0.001205 39  u=21 $air above moderator
c 15.245 cm moderator
   65   408  -2.635 -19  u=22 $detector
   66   256  -0.9300 -40 19  u=22 $moderator
   67     6 -0.001205 40  u=22 $air above moderator
c 22.865 cm moderator
   68   408  -2.635 -19  u=23 $detector
   69   256  -0.9300 -41 19  u=23 $moderator
   70     6 -0.001205 41  u=23 $air above moderator
c 0 cm moderator
   71   408  -2.635 -19  u=24 $detector
   72     6 -0.001205 19  u=24 $air above detector

c surfaces
c 1-6 Box defining void region
    1        pz 1030
    2        pz -26
    3        px 100
    4        px -100
    5        py 100
    6        py -100
c 7-12 Lattice Box
    7        pz 25
    8        pz -25
    9        px 10
   10        px -10
   11        py 10
   12        py -10
c   13        pz 25
c   14        pz -25
c 15-18 Lattice Cells
   15        px 2
   16        px -2
   17        py 2
   18        py -2
   19       rcc 0 0 -25 0 0 1 1  $detector
c 20-41 Moderators
   20       rpp -2 2 -2 2 -25 -22.455
   21       rpp -2 2 -2 2 -25 -21.82
   22       rpp -2 2 -2 2 -25 -21.185
   23       rpp -2 2 -2 2 -25 -20.55
   24       rpp -2 2 -2 2 -25 -19.915
```

```
   25       rpp -2 2 -2 2 -25 -19.28
   26       rpp -2 2 -2 2 -25 -18.645
   27       rpp -2 2 -2 2 -25 -18.01
   28       rpp -2 2 -2 2 -25 -17.375
   29       rpp -2 2 -2 2 -25 -16.74
   30       rpp -2 2 -2 2 -25 -16.105
   31       rpp -2 2 -2 2 -25 -15.47
   32       rpp -2 2 -2 2 -25 -14.835
   33       rpp -2 2 -2 2 -25 -14.2
   34       rpp -2 2 -2 2 -25 -13.565
   35       rpp -2 2 -2 2 -25 -12.93
   36       rpp -2 2 -2 2 -25 -12.295
   37       rpp -2 2 -2 2 -25 -11.66
   38       rpp -2 2 -2 2 -25 -11.025
   39       rpp -2 2 -2 2 -25 -10.39
   40       rpp -2 2 -2 2 -25 -9.755
   41       rpp -2 2 -2 2 -25 -2.135

mode n
c ---------------
c Materials
c ---------------
c     -- Mat  408 Lithium Fluoride --
c         density: 2.635E+00 g/cc
m408  3006.80c    -0.267585
      9019.80c    -0.732415
c     -- Mat  256  Polyethylene --
c         density: 9.300E-01 g/cc
m256  1001.80c    -0.143711
      6000.80c    -0.856289
c     -- Mat   6  Air-Dry --
c         density: 1.205E-03 g/cc
m6    6000.80c    -1.24e-04     7014.80c    -7.55268e-01
      8016.80c    -2.31781e-01  18036.80c   -1.2827e-02
imp:n  0            1 70r         $ 1, 72
c ----------------------------------------------------
c Source Description
c ----------------------------------------------------
sdef pos 0 0 45 x=d1 y=d2 z=1025 par=1 erg=14 vec=0 0 -1 dir=1
si1 -10 10 $ sampling range Xmin to Xmax
sp1  0  1  $ weighting for x sampling
si2 -10 10 $ sampling range Ymin to Ymax
sp2  0  1  $ weighting for y sampling
```

```
c sp3 -3
c
c      --------------------------------
c      Tally definitions
c      --------------------------------
fc24 Triton Production Rate in detector cells
f24:n (14<4[-2:2 -2:2 0:0]<2)
     (11<4[-2:2 -2:2 0:0]<2)
     (8<4[-2:2 -2:2 0:0]<2)
fm24 -1 408 105
nps 1e6
print
prdmp 0 0 1 0 0
```

5x5 Wedge Model MCNP Input Code

```
Detector Array 5x5
c cells
    1     0             1 :-2 :3 :-4 :5 :-6  $void
    2     6 -0.001205  -7 8 -9 10 -11 12  fill=1 $detector region
    3     6 -0.001205  #1 #2  $source region
    4     6 -0.001205 -15 16 -17 18  u=1 lat=1 $ROW 1 lattice definition
            fill=-2:2 -2:2 0:0
              11 12 13 14 15 $ROW 1
              11 12 13 14 15 $ROW 2
              11 12 13 14 15 $ROW 3
              11 12 13 14 15 $ROW 4
              11 12 13 14 15 $ROW 5
c ----------------------------------------------------
c Universe Key
c    Universe 1- Lattice Box
c    Universe 2- 2.545   cm moderator
c    Universe 3- 3.18    cm moderator
c    Universe 4- 3.815   cm moderator
c    Universe 5- 4.45    cm moderator
c    Universe 6- 5.085   cm moderator
c    Universe 7- 5.72    cm moderator
c    Universe 8- 6.355   cm moderator
c    Universe 9- 6.99    cm moderator
c    Universe 10- 7.625  cm moderator
c    Universe 11- 8.26   cm moderator
c    Universe 12- 8.895  cm moderator
c    Universe 13- 9.53   cm moderator
c    Universe 14- 10.165 cm moderator
```

```
c    Universe 15- 10.8   cm moderator
c    Universe 16- 11.435 cm moderator
c    Universe 17- 12.07  cm moderator
c    Universe 18- 12.705 cm moderator
c    Universe 19- 13.34  cm moderator
c    Universe 20- 13.975 cm moderator
c    Universe 21- 14.61  cm moderator
c    Universe 22- 15.245 cm moderator
c    Universe 23- 22.865 cm moderator
c    Universe 24- 0      cm moderator
c ----------------------------------------------------
c Moderators
c 2.545 cm moderator
    5   408  -2.635 -19  u=2 $detector
    6   256  -0.9300 -20 19  u=2 $moderator
    7     6 -0.001205 20  u=2 $air above moderator
c 3.18 cm moderator
    8   408  -2.635 -19  u=3 $detector
    9   256  -0.9300 -21 19  u=3 $moderator
   10     6 -0.001205 21  u=3 $air above moderator
c 3.815 cm moderator
   11   408  -2.635 -19  u=4 $detector
   12   256  -0.9300 -22 19  u=4 $moderator
   13     6 -0.001205 22  u=4 $air above moderator
c 4.45 cm moderator
   14   408  -2.635 -19  u=5 $detector
   15   256  -0.9300 -23 19  u=5 $moderator
   16     6 -0.001205 23  u=5 $air above moderator
c 5.085 cm moderator
   17   408  -2.635 -19  u=6 $detector
   18   256  -0.9300 -24 19  u=6 $moderator
   19     6 -0.001205 24  u=6 $air above moderator
c 5.72 cm moderator
   20   408  -2.635 -19  u=7 $detector
   21   256  -0.9300 -25 19  u=7 $moderator
   22     6 -0.001205 25  u=7 $air above moderator
c 6.355 cm moderator
   23   408  -2.635 -19  u=8 $detector
   24   256  -0.9300 -26 19  u=8 $moderator
   25     6 -0.001205 26  u=8 $air above moderator
c 6.99 cm moderator
   26   408  -2.635 -19  u=9 $detector
   27   256  -0.9300 -27 19  u=9 $moderator
```

```
   28     6 -0.001205 27  u=9 $air above moderator
c 7.625 cm moderator
   29   408  -2.635 -19  u=10 $detector
   30   256  -0.9300 -28 19  u=10 $moderator
   31     6 -0.001205 28  u=10 $air above moderator
c 8.26 cm moderator
   32   408  -2.635 -19  u=11 $detector
   33   256  -0.9300 -29 19  u=11 $moderator
   34     6 -0.001205 29  u=11 $air above moderator
c 8.895 cm moderator
   35   408  -2.635 -19  u=12 $detector
   36   256  -0.9300 -30 19  u=12 $moderator
   37     6 -0.001205 30  u=12 $air above moderator
c 9.53 cm moderator
   38   408  -2.635 -19  u=13 $detector
   39   256  -0.9300 -31 19  u=13 $moderator
   40     6 -0.001205 31  u=13 $air above moderator
c 10.165 cm moderator
   41   408  -2.635 -19  u=14 $detector
   42   256  -0.9300 -32 19  u=14 $moderator
   43     6 -0.001205 32  u=14 $air above moderator
c 10.8 cm moderator
   44   408  -2.635 -19  u=15 $detector
   45   256  -0.9300 -33 19  u=15 $moderator
   46     6 -0.001205 33  u=15 $air above moderator
c 11.435 cm moderator
   47   408  -2.635 -19  u=16 $detector
   48   256  -0.9300 -34 19  u=16 $moderator
   49     6 -0.001205 34  u=16 $air above moderator
c 12.07 cm moderator
   50   408  -2.635 -19  u=17 $detector
   51   256  -0.9300 -35 19  u=17 $moderator
   52     6 -0.001205 35  u=17 $air above moderator
c 12.705 cm moderator
   53   408  -2.635 -19  u=18 $detector
   54   256  -0.9300 -36 19  u=18 $moderator
   55     6 -0.001205 36  u=18 $air above moderator
c 13.34 cm moderator
   56   408  -2.635 -19  u=19 $detector
   57   256  -0.9300 -37 19  u=19 $moderator
   58     6 -0.001205 37  u=19 $air above moderator
c 13.975 cm moderator
   59   408  -2.635 -19  u=20 $detector
```

```
   60   256  -0.9300 -38 19  u=20 $moderator
   61     6 -0.001205 38  u=20 $air above moderator
c 14.61 cm moderator
   62   408  -2.635 -19  u=21 $detector
   63   256  -0.9300 -39 19  u=21 $moderator
   64     6 -0.001205 39  u=21 $air above moderator
c 15.245 cm moderator
   65   408  -2.635 -19  u=22 $detector
   66   256  -0.9300 -40 19  u=22 $moderator
   67     6 -0.001205 40  u=22 $air above moderator
c 22.865 cm moderator
   68   408  -2.635 -19  u=23 $detector
   69   256  -0.9300 -41 19  u=23 $moderator
   70     6 -0.001205 41  u=23 $air above moderator
c 0 cm moderator
   71   408  -2.635 -19  u=24 $detector
   72     6 -0.001205 19  u=24 $air above detector

c surfaces
c 1-6 Box defining void region
    1        pz 1030
    2        pz -26
    3        px 100
    4        px -100
    5        py 100
    6        py -100
c 7-12 Lattice Box
    7        pz 25
    8        pz -25
    9        px 10
   10        px -10
   11        py 10
   12        py -10
c   13        pz 25
c   14        pz -25
c 15-18 Lattice Cells
   15        px 2
   16        px -2
   17        py 2
   18        py -2
   19       rcc 0 0 -25 0 0 1 1  $detector
c 20-41 Moderators
   20       rpp -2 2 -2 2 -25 -22.455
```

```
   21       rpp -2 2 -2 2 -25 -21.82
   22       rpp -2 2 -2 2 -25 -21.185
   23       rpp -2 2 -2 2 -25 -20.55
   24       rpp -2 2 -2 2 -25 -19.915
   25       rpp -2 2 -2 2 -25 -19.28
   26       rpp -2 2 -2 2 -25 -18.645
   27       rpp -2 2 -2 2 -25 -18.01
   28       rpp -2 2 -2 2 -25 -17.375
   29       rpp -2 2 -2 2 -25 -16.74
   30       rpp -2 2 -2 2 -25 -16.105
   31       rpp -2 2 -2 2 -25 -15.47
   32       rpp -2 2 -2 2 -25 -14.835
   33       rpp -2 2 -2 2 -25 -14.2
   34       rpp -2 2 -2 2 -25 -13.565
   35       rpp -2 2 -2 2 -25 -12.93
   36       rpp -2 2 -2 2 -25 -12.295
   37       rpp -2 2 -2 2 -25 -11.66
   38       rpp -2 2 -2 2 -25 -11.025
   39       rpp -2 2 -2 2 -25 -10.39
   40       rpp -2 2 -2 2 -25 -9.755
   41       rpp -2 2 -2 2 -25 -2.135

mode n
c ---------------
c Materials
c ---------------
c     -- Mat  408 Lithium Fluoride --
c         density: 2.635E+00 g/cc
m408  3006.80c    -0.267585
      9019.80c    -0.732415
c     -- Mat  256  Polyethylene --
c         density: 9.300E-01 g/cc
m256  1001.80c    -0.143711
      6000.80c    -0.856289
c     -- Mat   6  Air-Dry --
c         density: 1.205E-03 g/cc
m6    6000.80c    -1.24e-04     7014.80c    -7.55268e-01
      8016.80c    -2.31781e-01  18036.80c   -1.2827e-02
imp:n  0            1 70r         $ 1, 72
c ----------------------------------------------------
c Source Description
c ----------------------------------------------------
sdef pos 0 0 45 x=d1 y=d2 z=1025 par=1 erg=1 vec=0 0 -1 dir=1
```

```
si1 -10 10 $ sampling range Xmin to Xmax
sp1  0  1  $ weighting for x sampling
si2 -10 10 $ sampling range Ymin to Ymax
sp2  0  1  $ weighting for y sampling
c sp3 -3
c
c      --------------------------------
c      Tally definitions
c      --------------------------------
fc24 Triton Production Rate in detector cells
f24:n (32<4[-2:2 -2:2 0:0]<2)
     (35<4[-2:2 -2:2 0:0]<2)
         (38<4[-2:2 -2:2 0:0]<2)
         (41<4[-2:2 -2:2 0:0]<2)
         (44<4[-2:2 -2:2 0:0]<2)
fm24 -1 408 105
nps 1e6
print
prdmp 0 0 1 0 0
```

5x5 Opposite Wedge Model MCNP Input Code

```
Detector Array 5x5
c cells
    1     0             1 :-2 :3 :-4 :5 :-6  $void
    2     6 -0.001205  -7 8 -9 10 -11 12  fill=1 $detector region
    3     6 -0.001205  #1 #2  $source region
    4     6 -0.001205 -15 16 -17 18  u=1 lat=1 $ROW 1 lattice definition
            fill=-2:2 -2:2 0:0
      24 2 3 4  5  $ROW 1
       5 4 3 2 24  $ROW 2
      24 2 3 4  5  $ROW 3
       5 4 3 2 24  $ROW 4
      24 2 3 4  5  $ROW 5
c ----------------------------------------------------
c Universe Key
c    Universe 1- Lattice Box
c    Universe 2- 2.545   cm moderator
c    Universe 3- 3.18    cm moderator
c    Universe 4- 3.815   cm moderator
c    Universe 5- 4.45    cm moderator
c    Universe 6- 5.085   cm moderator
c    Universe 7- 5.72    cm moderator
c    Universe 8- 6.355   cm moderator
```

```
c    Universe 9- 6.99    cm moderator
c    Universe 10- 7.625  cm moderator
c    Universe 11- 8.26   cm moderator
c    Universe 12- 8.895  cm moderator
c    Universe 13- 9.53   cm moderator
c    Universe 14- 10.165 cm moderator
c    Universe 15- 10.8   cm moderator
c    Universe 16- 11.435 cm moderator
c    Universe 17- 12.07  cm moderator
c    Universe 18- 12.705 cm moderator
c    Universe 19- 13.34  cm moderator
c    Universe 20- 13.975 cm moderator
c    Universe 21- 14.61  cm moderator
c    Universe 22- 15.245 cm moderator
c    Universe 23- 22.865 cm moderator
c    Universe 24- 0      cm moderator
c ----------------------------------------------------
c Moderators
c 2.545 cm moderator
    5   408  -2.635 -19  u=2 $detector
    6   256  -0.9300 -20 19  u=2 $moderator
    7     6 -0.001205 20  u=2 $air above moderator
c 3.18 cm moderator
    8   408  -2.635 -19  u=3 $detector
    9   256  -0.9300 -21 19  u=3 $moderator
   10     6 -0.001205 21  u=3 $air above moderator
c 3.815 cm moderator
   11   408  -2.635 -19  u=4 $detector
   12   256  -0.9300 -22 19  u=4 $moderator
   13     6 -0.001205 22  u=4 $air above moderator
c 4.45 cm moderator
   14   408  -2.635 -19  u=5 $detector
   15   256  -0.9300 -23 19  u=5 $moderator
   16     6 -0.001205 23  u=5 $air above moderator
c 5.085 cm moderator
   17   408  -2.635 -19  u=6 $detector
   18   256  -0.9300 -24 19  u=6 $moderator
   19     6 -0.001205 24  u=6 $air above moderator
c 5.72 cm moderator
   20   408  -2.635 -19  u=7 $detector
   21   256  -0.9300 -25 19  u=7 $moderator
   22     6 -0.001205 25  u=7 $air above moderator
c 6.355 cm moderator
```

```
   23   408  -2.635 -19  u=8 $detector
   24   256  -0.9300 -26 19  u=8 $moderator
   25     6 -0.001205 26  u=8 $air above moderator
c 6.99 cm moderator
   26   408  -2.635 -19  u=9 $detector
   27   256  -0.9300 -27 19  u=9 $moderator
   28     6 -0.001205 27  u=9 $air above moderator
c 7.625 cm moderator
   29   408  -2.635 -19  u=10 $detector
   30   256  -0.9300 -28 19  u=10 $moderator
   31     6 -0.001205 28  u=10 $air above moderator
c 8.26 cm moderator
   32   408  -2.635 -19  u=11 $detector
   33   256  -0.9300 -29 19  u=11 $moderator
   34     6 -0.001205 29  u=11 $air above moderator
c 8.895 cm moderator
   35   408  -2.635 -19  u=12 $detector
   36   256  -0.9300 -30 19  u=12 $moderator
   37     6 -0.001205 30  u=12 $air above moderator
c 9.53 cm moderator
   38   408  -2.635 -19  u=13 $detector
   39   256  -0.9300 -31 19  u=13 $moderator
   40     6 -0.001205 31  u=13 $air above moderator
c 10.165 cm moderator
   41   408  -2.635 -19  u=14 $detector
   42   256  -0.9300 -32 19  u=14 $moderator
   43     6 -0.001205 32  u=14 $air above moderator
c 10.8 cm moderator
   44   408  -2.635 -19  u=15 $detector
   45   256  -0.9300 -33 19  u=15 $moderator
   46     6 -0.001205 33  u=15 $air above moderator
c 11.435 cm moderator
   47   408  -2.635 -19  u=16 $detector
   48   256  -0.9300 -34 19  u=16 $moderator
   49     6 -0.001205 34  u=16 $air above moderator
c 12.07 cm moderator
   50   408  -2.635 -19  u=17 $detector
   51   256  -0.9300 -35 19  u=17 $moderator
   52     6 -0.001205 35  u=17 $air above moderator
c 12.705 cm moderator
   53   408  -2.635 -19  u=18 $detector
   54   256  -0.9300 -36 19  u=18 $moderator
   55     6 -0.001205 36  u=18 $air above moderator
```

```
c 13.34 cm moderator
   56   408  -2.635 -19  u=19 $detector
   57   256  -0.9300 -37 19  u=19 $moderator
   58     6 -0.001205 37  u=19 $air above moderator
c 13.975 cm moderator
   59   408  -2.635 -19  u=20 $detector
   60   256  -0.9300 -38 19  u=20 $moderator
   61     6 -0.001205 38  u=20 $air above moderator
c 14.61 cm moderator
   62   408  -2.635 -19  u=21 $detector
   63   256  -0.9300 -39 19  u=21 $moderator
   64     6 -0.001205 39  u=21 $air above moderator
c 15.245 cm moderator
   65   408  -2.635 -19  u=22 $detector
   66   256  -0.9300 -40 19  u=22 $moderator
   67     6 -0.001205 40  u=22 $air above moderator
c 22.865 cm moderator
   68   408  -2.635 -19  u=23 $detector
   69   256  -0.9300 -41 19  u=23 $moderator
   70     6 -0.001205 41  u=23 $air above moderator
c 0 cm moderator
   71   408  -2.635 -19  u=24 $detector
   72     6 -0.001205 19  u=24 $air above detector

c surfaces
c 1-6 Box defining void region
    1        pz 1030
    2        pz -26
    3        px 100
    4        px -100
    5        py 100
    6        py -100
c 7-12 Lattice Box
    7        pz 25
    8        pz -25
    9        px 10
   10        px -10
   11        py 10
   12        py -10
c   13        pz 25
c   14        pz -25
c 15-18 Lattice Cells
   15        px 2
```

```
   16        px -2
   17        py 2
   18        py -2
   19       rcc 0 0 -25 0 0 1 1  $detector
c 20-41 Moderators
   20       rpp -2 2 -2 2 -25 -22.455
   21       rpp -2 2 -2 2 -25 -21.82
   22       rpp -2 2 -2 2 -25 -21.185
   23       rpp -2 2 -2 2 -25 -20.55
   24       rpp -2 2 -2 2 -25 -19.915
   25       rpp -2 2 -2 2 -25 -19.28
   26       rpp -2 2 -2 2 -25 -18.645
   27       rpp -2 2 -2 2 -25 -18.01
   28       rpp -2 2 -2 2 -25 -17.375
   29       rpp -2 2 -2 2 -25 -16.74
   30       rpp -2 2 -2 2 -25 -16.105
   31       rpp -2 2 -2 2 -25 -15.47
   32       rpp -2 2 -2 2 -25 -14.835
   33       rpp -2 2 -2 2 -25 -14.2
   34       rpp -2 2 -2 2 -25 -13.565
   35       rpp -2 2 -2 2 -25 -12.93
   36       rpp -2 2 -2 2 -25 -12.295
   37       rpp -2 2 -2 2 -25 -11.66
   38       rpp -2 2 -2 2 -25 -11.025
   39       rpp -2 2 -2 2 -25 -10.39
   40       rpp -2 2 -2 2 -25 -9.755
   41       rpp -2 2 -2 2 -25 -2.135

mode n
c ---------------
c Materials
c ---------------
c     -- Mat  408 Lithium Fluoride --
c         density: 2.635E+00 g/cc
m408  3006.80c    -0.267585
      9019.80c    -0.732415
c     -- Mat  256  Polyethylene --
c         density: 9.300E-01 g/cc
m256  1001.80c    -0.143711
      6000.80c    -0.856289
c     -- Mat   6  Air-Dry --
c         density: 1.205E-03 g/cc
m6    6000.80c    -1.24e-04     7014.80c    -7.55268e-01
```

```
     8016.80c    -2.31781e-01  18036.80c   -1.2827e-02
imp:n  0            1 70r         $ 1, 72
c -------------------------------------------------------
c Source Description
c -------------------------------------------------------
sdef pos 0 0 45 x=d1 y=d2 z=1025 par=1 erg=1e-8 vec=0 0 -1 dir=1
si1 -10 10 $ sampling range Xmin to Xmax
sp1  0  1  $ weighting for x sampling
si2 -10 10 $ sampling range Ymin to Ymax
sp2  0  1  $ weighting for y sampling
c sp3 -3
c
c      --------------------------------
c      Tally definitions
c      --------------------------------
fc24 Triton Production Rate in detector cells
f24:n (71<4[-2:2 -2:2 0:0]<2)
     (5<4[-2:2 -2:2 0:0]<2)
     (8<4[-2:2 -2:2 0:0]<2)
     (11<4[-2:2 -2:2 0:0]<2)
     (14<4[-2:2 -2:2 0:0]<2)
fm24 -1 408 105
nps 1e7
print
prdmp 0 0 1 0 0
```

5x25 Detector Array MCNP Input Code

```
Pyramid Li-6 Detector Array 5x25
c cells
    1     0           1 :-2 :3 :-4 :5 :-6  $void
    2     6 -0.001205 -7 8 -9 10 -11 12  fill=1 $detector region
    3     6 -0.001205 #1 #2  $source region
    4     6 -0.001205 -15 16 -17 18  u=1 lat=1 $ROW 1 lattice definition
            fill=-12:12 -2:2 0:0
      24  24  24  24  24   2   2   2   2   2   7   7   7   7   7  13  13  13
             13  13  15  15  15  15  15  $ROW 1
      24   2   2   2  24   2   3   3   3   2   7   8   8   8   7  13  14  14
             14  13  15  16  16  16  15  $ROW 2
      24   2   3   2  24   2   3   4   3   2   7   8   9   8   7  13  14  15
             14  13  15  16  17  16  15  $ROW 3
      24   2   2   2  24   2   3   3   3   2   7   8   8   8   7  13  14  14
             14  13  15  16  16  16  15  $ROW 4
      24  24  24  24  24   2   2   2   2   2   7   7   7   7   7  13  13  13
```

```
            13  13  15  15  15  15  15  $ROW 5
c ----------------------------------------------------
c Universe Key
c    Universe 1- Lattice Box
c    Universe 2- 2.545   cm moderator
c    Universe 3- 3.18    cm moderator
c    Universe 4- 3.815   cm moderator
c    Universe 5- 4.45    cm moderator
c    Universe 6- 5.085   cm moderator
c    Universe 7- 5.72    cm moderator
c    Universe 8- 6.355   cm moderator
c    Universe 9- 6.99    cm moderator
c    Universe 10- 7.625  cm moderator
c    Universe 11- 8.26   cm moderator
c    Universe 12- 8.895  cm moderator
c    Universe 13- 9.53   cm moderator
c    Universe 14- 10.165 cm moderator
c    Universe 15- 10.8   cm moderator
c    Universe 16- 11.435 cm moderator
c    Universe 17- 12.07  cm moderator
c    Universe 18- 12.705 cm moderator
c    Universe 19- 13.34  cm moderator
c    Universe 20- 13.975 cm moderator
c    Universe 21- 14.61  cm moderator
c    Universe 22- 15.245 cm moderator
c    Universe 23- 22.865 cm moderator
c    Universe 24- 0      cm moderator
c ----------------------------------------------------
c Moderators
c 2.545 cm moderator
    5   408  -2.635 -19  u=2 $detector
    6   256  -0.9300 -20 19  u=2 $moderator
    7     6 -0.001205 20  u=2 $air above moderator
c 3.18 cm moderator
    8   408  -2.635 -19  u=3 $detector
    9   256  -0.9300 -21 19  u=3 $moderator
   10     6 -0.001205 21  u=3 $air above moderator
c 3.815 cm moderator
   11   408  -2.635 -19  u=4 $detector
   12   256  -0.9300 -22 19  u=4 $moderator
   13     6 -0.001205 22  u=4 $air above moderator
c 4.45 cm moderator
   14   408  -2.635 -19  u=5 $detector
```

```
   15   256  -0.9300 -23 19  u=5 $moderator
   16     6 -0.001205 23  u=5 $air above moderator
c 5.085 cm moderator
   17   408  -2.635 -19  u=6 $detector
   18   256  -0.9300 -24 19  u=6 $moderator
   19     6 -0.001205 24  u=6 $air above moderator
c 5.72 cm moderator
   20   408  -2.635 -19  u=7 $detector
   21   256  -0.9300 -25 19  u=7 $moderator
   22     6 -0.001205 25  u=7 $air above moderator
c 6.355 cm moderator
   23   408  -2.635 -19  u=8 $detector
   24   256  -0.9300 -26 19  u=8 $moderator
   25     6 -0.001205 26  u=8 $air above moderator
c 6.99 cm moderator
   26   408  -2.635 -19  u=9 $detector
   27   256  -0.9300 -27 19  u=9 $moderator
   28     6 -0.001205 27  u=9 $air above moderator
c 7.625 cm moderator
   29   408  -2.635 -19  u=10 $detector
   30   256  -0.9300 -28 19  u=10 $moderator
   31     6 -0.001205 28  u=10 $air above moderator
c 8.26 cm moderator
   32   408  -2.635 -19  u=11 $detector
   33   256  -0.9300 -29 19  u=11 $moderator
   34     6 -0.001205 29  u=11 $air above moderator
c 8.895 cm moderator
   35   408  -2.635 -19  u=12 $detector
   36   256  -0.9300 -30 19  u=12 $moderator
   37     6 -0.001205 30  u=12 $air above moderator
c 9.53 cm moderator
   38   408  -2.635 -19  u=13 $detector
   39   256  -0.9300 -31 19  u=13 $moderator
   40     6 -0.001205 31  u=13 $air above moderator
c 10.165 cm moderator
   41   408  -2.635 -19  u=14 $detector
   42   256  -0.9300 -32 19  u=14 $moderator
   43     6 -0.001205 32  u=14 $air above moderator
c 10.8 cm moderator
   44   408  -2.635 -19  u=15 $detector
   45   256  -0.9300 -33 19  u=15 $moderator
   46     6 -0.001205 33  u=15 $air above moderator
c 11.435 cm moderator
```

```
   47   408  -2.635 -19  u=16 $detector
   48   256  -0.9300 -34 19  u=16 $moderator
   49     6 -0.001205 34  u=16 $air above moderator
c 12.07 cm moderator
   50   408  -2.635 -19  u=17 $detector
   51   256  -0.9300 -35 19  u=17 $moderator
   52     6 -0.001205 35  u=17 $air above moderator
c 12.705 cm moderator
   53   408  -2.635 -19  u=18 $detector
   54   256  -0.9300 -36 19  u=18 $moderator
   55     6 -0.001205 36  u=18 $air above moderator
c 13.34 cm moderator
   56   408  -2.635 -19  u=19 $detector
   57   256  -0.9300 -37 19  u=19 $moderator
   58     6 -0.001205 37  u=19 $air above moderator
c 13.975 cm moderator
   59   408  -2.635 -19  u=20 $detector
   60   256  -0.9300 -38 19  u=20 $moderator
   61     6 -0.001205 38  u=20 $air above moderator
c 14.61 cm moderator
   62   408  -2.635 -19  u=21 $detector
   63   256  -0.9300 -39 19  u=21 $moderator
   64     6 -0.001205 39  u=21 $air above moderator
c 15.245 cm moderator
   65   408  -2.635 -19  u=22 $detector
   66   256  -0.9300 -40 19  u=22 $moderator
   67     6 -0.001205 40  u=22 $air above moderator
c 22.865 cm moderator
   68   408  -2.635 -19  u=23 $detector
   69   256  -0.9300 -41 19  u=23 $moderator
   70     6 -0.001205 41  u=23 $air above moderator
c 0 cm moderator
   71   408  -2.635 -19  u=24 $detector
   72     6 -0.001205 19  u=24 $air above detector

c surfaces
c 1-6 Box defining void region
    1        pz 1030
    2        pz -26
    3        px 100
    4        px -100
    5        py 100
    6        py -100
```

```
c 7-12 Lattice Box
    7        pz 25
    8        pz -25
    9        px 50
   10        px -50
   11        py 10
   12        py -10
c   13        pz 25
c   14        pz -25
c 15-18 Lattice Cells
   15        px 2
   16        px -2
   17        py 2
   18        py -2
   19       rcc 0 0 -25 0 0 1 1  $detector
c 20-41 Moderators
   20       rpp -2 2 -2 2 -25 -22.455
   21       rpp -2 2 -2 2 -25 -21.82
   22       rpp -2 2 -2 2 -25 -21.185
   23       rpp -2 2 -2 2 -25 -20.55
   24       rpp -2 2 -2 2 -25 -19.915
   25       rpp -2 2 -2 2 -25 -19.28
   26       rpp -2 2 -2 2 -25 -18.645
   27       rpp -2 2 -2 2 -25 -18.01
   28       rpp -2 2 -2 2 -25 -17.375
   29       rpp -2 2 -2 2 -25 -16.74
   30       rpp -2 2 -2 2 -25 -16.105
   31       rpp -2 2 -2 2 -25 -15.47
   32       rpp -2 2 -2 2 -25 -14.835
   33       rpp -2 2 -2 2 -25 -14.2
   34       rpp -2 2 -2 2 -25 -13.565
   35       rpp -2 2 -2 2 -25 -12.93
   36       rpp -2 2 -2 2 -25 -12.295
   37       rpp -2 2 -2 2 -25 -11.66
   38       rpp -2 2 -2 2 -25 -11.025
   39       rpp -2 2 -2 2 -25 -10.39
   40       rpp -2 2 -2 2 -25 -9.755
   41       rpp -2 2 -2 2 -25 -2.135

mode n
c ---------------
c Materials
c ---------------
```

```
c     -- Mat  408 Lithium Fluoride --
c         density: 2.635E+00 g/cc
m408  3006.80c    -0.267585
      9019.80c    -0.732415
c     -- Mat  256  Polyethylene --
c         density: 9.300E-01 g/cc
m256  1001.80c    -0.143711
      6000.80c    -0.856289
c     -- Mat   6  Air-Dry --
c         density: 1.205E-03 g/cc
m6    6000.80c    -1.24e-04     7014.80c    -7.55268e-01
      8016.80c    -2.31781e-01  18036.80c   -1.2827e-02
imp:n  0            1 70r         $ 1, 72
c -----------------------------------------------------
c Source Description
c -----------------------------------------------------
sdef pos=0 0 0 x=d1 y=d2 z=1025 par=1 erg=10 vec=0 0 -1 dir=1
si1 -50 50 $ sampling range Xmin to Xmax
sp1  0  1  $ weighting for x sampling
si2 -10 10 $ sampling range Ymin to Ymax
sp2  0  1  $ weighting for y sampling
c sp3 -3
c
c      --------------------------------
c      Tally definitions
c      --------------------------------
fc24 Triton Production Rate in detector cells
f24:n (71<4[-12:-8 -2:2 0:0]<2) $p24
     (5<4[-12:-8 -2:2 0:0]<2)   $p24
     (8<4[-12:-8 -2:2 0:0]<2)   $p24
     (5<4[-7:-3 -2:2 0:0]<2)    $p2
     (8<4[-7:-3 -2:2 0:0]<2)    $p2
     (11<4[-7:-3 -2:2 0:0]<2)   $p2
     (20<4[-2:2 -2:2 0:0]<2)    $p7
     (23<4[-2:2 -2:2 0:0]<2)    $p7
     (26<4[-2:2 -2:2 0:0]<2)    $p7
     (38<4[3:7 -2:2 0:0]<2)     $p13
     (41<4[3:7 -2:2 0:0]<2)     $p13
     (44<4[3:7 -2:2 0:0]<2)     $p13
     (44<4[8:12 -2:2 0:0]<2)    $p15
     (47<4[8:12 -2:2 0:0]<2)    $p15
     (50<4[8:12 -2:2 0:0]<2)    $p15
fm24 -1 408 105
```

```
nps 1e8
print
prdmp 0 0 1 0 0
```

5x25 Detector Array with Space Between Moderators and Detectors MCNP Input Code

```
Pyramid Li-6 Detector Array 5x25
c cells
    1     0           1 :-2 :3 :-4 :5 :-6  $void
    2     6 -0.001205 -7 8 -9 10 -11 12  fill=1 $detector region
    3     6 -0.001205 #1 #2  $source region
    4     6 -0.001205 -15 16 -17 18  u=1 lat=1 $ROW 1 lattice definition
            fill=-12:12 -2:2 0:0
      24  24  24  24  24   2   2   2   2   2   7   7   7   7   7  13  13  13
             13  13  15  15  15  15  15  $ROW 1
      24   2   2   2  24   2   3   3   3   2   7   8   8   8   7  13  14  14
             14  13  15  16  16  16  15  $ROW 2
      24   2   3   2  24   2   3   4   3   2   7   8   9   8   7  13  14  15
             14  13  15  16  17  16  15  $ROW 3
      24   2   2   2  24   2   3   3   3   2   7   8   8   8   7  13  14  14
             14  13  15  16  16  16  15  $ROW 4
      24  24  24  24  24   2   2   2   2   2   7   7   7   7   7  13  13  13
             13  13  15  15  15  15  15  $ROW 5
c ------------------------------------------------------
c Universe Key
c    Universe 1- Lattice Box
c    Universe 2- 2.545   cm moderator
c    Universe 3- 3.18    cm moderator
c    Universe 4- 3.815   cm moderator
c    Universe 5- 4.45    cm moderator
c    Universe 6- 5.085   cm moderator
c    Universe 7- 5.72    cm moderator
c    Universe 8- 6.355   cm moderator
c    Universe 9- 6.99    cm moderator
c    Universe 10- 7.625  cm moderator
c    Universe 11- 8.26   cm moderator
c    Universe 12- 8.895  cm moderator
c    Universe 13- 9.53   cm moderator
c    Universe 14- 10.165 cm moderator
c    Universe 15- 10.8   cm moderator
c    Universe 16- 11.435 cm moderator
c    Universe 17- 12.07  cm moderator
c    Universe 18- 12.705 cm moderator
```

```
c    Universe 19- 13.34  cm moderator
c    Universe 20- 13.975 cm moderator
c    Universe 21- 14.61  cm moderator
c    Universe 22- 15.245 cm moderator
c    Universe 23- 22.865 cm moderator
c    Universe 24- 0      cm moderator
c ----------------------------------------------------
c Moderators
c 2.545 cm moderator
    5   408  -2.635 -19  u=2 $detector
    6   256  -0.9300 -20 u=2 $moderator
    7      6 -0.001205 20 19 u=2 $air above moderator
c 3.18 cm moderator
    8   408  -2.635 -19  u=3 $detector
    9   256  -0.9300 -21   u=3 $moderator
   10      6 -0.001205 21 19 u=3 $air above moderator
c 3.815 cm moderator
   11   408  -2.635 -19  u=4 $detector
   12   256  -0.9300 -22   u=4 $moderator
   13      6 -0.001205 22 19 u=4 $air above moderator
c 4.45 cm moderator
   14   408  -2.635 -19  u=5 $detector
   15   256  -0.9300 -23   u=5 $moderator
   16      6 -0.001205 23 19 u=5 $air above moderator
c 5.085 cm moderator
   17   408  -2.635 -19  u=6 $detector
   18   256  -0.9300 -24   u=6 $moderator
   19      6 -0.001205 24 19 u=6 $air above moderator
c 5.72 cm moderator
   20   408  -2.635 -19  u=7 $detector
   21   256  -0.9300 -25   u=7 $moderator
   22      6 -0.001205 25 19 u=7 $air above moderator
c 6.355 cm moderator
   23   408  -2.635 -19  u=8 $detector
   24   256  -0.9300 -26   u=8 $moderator
   25      6 -0.001205 26 19 u=8 $air above moderator
c 6.99 cm moderator
   26   408  -2.635 -19  u=9 $detector
   27   256  -0.9300 -27   u=9 $moderator
   28      6 -0.001205 27 19 u=9 $air above moderator
c 7.625 cm moderator
   29   408  -2.635 -19  u=10 $detector
   30   256  -0.9300 -28   u=10 $moderator
```

```
   31     6 -0.001205 28 19 u=10 $air above moderator
c 8.26 cm moderator
   32   408  -2.635 -19  u=11 $detector
   33   256  -0.9300 -29   u=11 $moderator
   34     6 -0.001205 29 19 u=11 $air above moderator
c 8.895 cm moderator
   35   408  -2.635 -19  u=12 $detector
   36   256  -0.9300 -30   u=12 $moderator
   37     6 -0.001205 30 19 u=12 $air above moderator
c 9.53 cm moderator
   38   408  -2.635 -19  u=13 $detector
   39   256  -0.9300 -31   u=13 $moderator
   40     6 -0.001205 31 19 u=13 $air above moderator
c 10.165 cm moderator
   41   408  -2.635 -19  u=14 $detector
   42   256  -0.9300 -32   u=14 $moderator
   43     6 -0.001205 32 19 u=14 $air above moderator
c 10.8 cm moderator
   44   408  -2.635 -19  u=15 $detector
   45   256  -0.9300 -33   u=15 $moderator
   46     6 -0.001205 33 19 u=15 $air above moderator
c 11.435 cm moderator
   47   408  -2.635 -19  u=16 $detector
   48   256  -0.9300 -34   u=16 $moderator
   49     6 -0.001205 34 19 u=16 $air above moderator
c 12.07 cm moderator
   50   408  -2.635 -19  u=17 $detector
   51   256  -0.9300 -35   u=17 $moderator
   52     6 -0.001205 35 19 u=17 $air above moderator
c 12.705 cm moderator
   53   408  -2.635 -19  u=18 $detector
   54   256  -0.9300 -36   u=18 $moderator
   55     6 -0.001205 36 19 u=18 $air above moderator
c 13.34 cm moderator
   56   408  -2.635 -19  u=19 $detector
   57   256  -0.9300 -37   u=19 $moderator
   58     6 -0.001205 37 19 u=19 $air above moderator
c 13.975 cm moderator
   59   408  -2.635 -19  u=20 $detector
   60   256  -0.9300 -38   u=20 $moderator
   61     6 -0.001205 38 19 u=20 $air above moderator
c 14.61 cm moderator
   62   408  -2.635 -19  u=21 $detector
```

```
   63   256  -0.9300 -39   u=21 $moderator
   64     6 -0.001205 39 19 u=21 $air above moderator
c 15.245 cm moderator
   65   408  -2.635 -19  u=22 $detector
   66   256  -0.9300 -40   u=22 $moderator
   67     6 -0.001205 40 19 u=22 $air above moderator
c 22.865 cm moderator
   68   408  -2.635 -19  u=23 $detector
   69   256  -0.9300 -41   u=23 $moderator
   70     6 -0.001205 41 19 u=23 $air above moderator
c 0 cm moderator
   71   408  -2.635 -19  u=24 $detector
   72     6 -0.001205 19  u=24 $air above detector

c surfaces
c 1-6 Box defining void region
    1        pz 1030
    2        pz -46
    3        px 100
    4        px -100
    5        py 100
    6        py -100
c 7-12 Lattice Box
    7        pz 25
    8        pz -45
    9        px 50
   10        px -50
   11        py 10
   12        py -10
c 15-18 Lattice Cells
   15        px 2
   16        px -2
   17        py 2
   18        py -2
   19       rcc 0 0 -41.24 0 0 1 1  $detector
c 20-41 Moderators
   20       rpp -2 2 -2 2 -25 -22.455
   21       rpp -2 2 -2 2 -25 -21.82
   22       rpp -2 2 -2 2 -25 -21.185
   23       rpp -2 2 -2 2 -25 -20.55
   24       rpp -2 2 -2 2 -25 -19.915
   25       rpp -2 2 -2 2 -25 -19.28
   26       rpp -2 2 -2 2 -25 -18.645
```

```
   27       rpp -2 2 -2 2 -25 -18.01
   28       rpp -2 2 -2 2 -25 -17.375
   29       rpp -2 2 -2 2 -25 -16.74
   30       rpp -2 2 -2 2 -25 -16.105
   31       rpp -2 2 -2 2 -25 -15.47
   32       rpp -2 2 -2 2 -25 -14.835
   33       rpp -2 2 -2 2 -25 -14.2
   34       rpp -2 2 -2 2 -25 -13.565
   35       rpp -2 2 -2 2 -25 -12.93
   36       rpp -2 2 -2 2 -25 -12.295
   37       rpp -2 2 -2 2 -25 -11.66
   38       rpp -2 2 -2 2 -25 -11.025
   39       rpp -2 2 -2 2 -25 -10.39
   40       rpp -2 2 -2 2 -25 -9.755
   41       rpp -2 2 -2 2 -25 -2.135

mode n
c ---------------
c Materials
c ---------------
c     -- Mat  408 Lithium Fluoride --
c         density: 2.635E+00 g/cc
m408  3006.80c    -0.267585
      9019.80c    -0.732415
c     -- Mat  256  Polyethylene --
c         density: 9.300E-01 g/cc
m256  1001.80c    -0.143711
      6000.80c    -0.856289
c     -- Mat   6  Air-Dry --
c         density: 1.205E-03 g/cc
m6    6000.80c    -1.24e-04     7014.80c    -7.55268e-01
      8016.80c    -2.31781e-01  18036.80c   -1.2827e-02
imp:n  0            1 70r         $ 1, 72
c -------------------------------------------------------
c Source Description
c -------------------------------------------------------
sdef pos=0 0 0 x=d1 y=d2 z=1025 par=1 erg=14 vec=0 0 -1 dir=1
si1 -50 50 $ sampling range Xmin to Xmax
sp1  0  1  $ weighting for x sampling
si2 -10 10 $ sampling range Ymin to Ymax
sp2  0  1  $ weighting for y sampling
c sp3 -3
c
```

```
c      --------------------------------
c      Tally definitions
c      --------------------------------
fc24 Triton Production Rate in detector cells
f24:n (71<4[-12:-8 -2:2 0:0]<2) $p24
     (5<4[-12:-8 -2:2 0:0]<2)   $p24
     (8<4[-12:-8 -2:2 0:0]<2)   $p24
     (5<4[-7:-3 -2:2 0:0]<2)    $p2
     (8<4[-7:-3 -2:2 0:0]<2)    $p2
     (11<4[-7:-3 -2:2 0:0]<2)   $p2
     (20<4[-2:2 -2:2 0:0]<2)    $p7
     (23<4[-2:2 -2:2 0:0]<2)    $p7
     (26<4[-2:2 -2:2 0:0]<2)    $p7
     (38<4[3:7 -2:2 0:0]<2)     $p13
     (41<4[3:7 -2:2 0:0]<2)     $p13
     (44<4[3:7 -2:2 0:0]<2)     $p13
     (44<4[8:12 -2:2 0:0]<2)    $p15
     (47<4[8:12 -2:2 0:0]<2)    $p15
     (50<4[8:12 -2:2 0:0]<2)    $p15
fm24 -1 408 105
nps 1e8
print
prdmp 0 0 1 0 0
```

5x25 Detector Array with 2.54 Polyethylene Layer Behind Detector Array MCNP Input Code

```
Pyramid Li-6 Detector Array 5x25
c cells
    1     0          1 :-2 :3 :-4 :5 :-6  $void
    2     6 -0.001205 -7 8 -9 10 -11 12  fill=1 $detector region
    3     6 -0.001205 #1 #2 #73 $source region
    4     6 -0.001205 -15 16 -17 18  u=1 lat=1 $ROW 1 lattice definition
            fill=-12:12 -2:2 0:0
      24  24  24  24  24   2   2   2   2   2   7   7   7   7   7  13  13  13
             13  13  15  15  15  15  15  $ROW 1
      24   2   2   2  24   2   3   3   3   2   7   8   8   8   7  13  14  14
             14  13  15  16  16  16  15  $ROW 2
      24   2   3   2  24   2   3   4   3   2   7   8   9   8   7  13  14  15
             14  13  15  16  17  16  15  $ROW 3
      24   2   2   2  24   2   3   3   3   2   7   8   8   8   7  13  14  14
             14  13  15  16  16  16  15  $ROW 4
      24  24  24  24  24   2   2   2   2   2   7   7   7   7   7  13  13  13
```

```
            13  13  15  15  15  15  15  $ROW 5
c ---------------------------------------------------
c Universe Key
c    Universe 1- Lattice Box
c    Universe 2- 2.545   cm moderator
c    Universe 3- 3.18    cm moderator
c    Universe 4- 3.815   cm moderator
c    Universe 5- 4.45    cm moderator
c    Universe 6- 5.085   cm moderator
c    Universe 7- 5.72    cm moderator
c    Universe 8- 6.355   cm moderator
c    Universe 9- 6.99    cm moderator
c    Universe 10- 7.625  cm moderator
c    Universe 11- 8.26   cm moderator
c    Universe 12- 8.895  cm moderator
c    Universe 13- 9.53   cm moderator
c    Universe 14- 10.165 cm moderator
c    Universe 15- 10.8   cm moderator
c    Universe 16- 11.435 cm moderator
c    Universe 17- 12.07  cm moderator
c    Universe 18- 12.705 cm moderator
c    Universe 19- 13.34  cm moderator
c    Universe 20- 13.975 cm moderator
c    Universe 21- 14.61  cm moderator
c    Universe 22- 15.245 cm moderator
c    Universe 23- 22.865 cm moderator
c    Universe 24- 0      cm moderator
c ---------------------------------------------------
c Moderators
c 2.545 cm moderator
    5   408  -2.635 -19  u=2 $detector
    6   256  -0.9300 -20 19  u=2 $moderator
    7     6 -0.001205 20  u=2 $air above moderator
c 3.18 cm moderator
    8   408  -2.635 -19  u=3 $detector
    9   256  -0.9300 -21 19  u=3 $moderator
   10     6 -0.001205 21  u=3 $air above moderator
c 3.815 cm moderator
   11   408  -2.635 -19  u=4 $detector
   12   256  -0.9300 -22 19  u=4 $moderator
   13     6 -0.001205 22  u=4 $air above moderator
c 4.45 cm moderator
   14   408  -2.635 -19  u=5 $detector
```

```
   15   256  -0.9300 -23 19  u=5 $moderator
   16     6 -0.001205 23  u=5 $air above moderator
c 5.085 cm moderator
   17   408  -2.635 -19  u=6 $detector
   18   256  -0.9300 -24 19  u=6 $moderator
   19     6 -0.001205 24  u=6 $air above moderator
c 5.72 cm moderator
   20   408  -2.635 -19  u=7 $detector
   21   256  -0.9300 -25 19  u=7 $moderator
   22     6 -0.001205 25  u=7 $air above moderator
c 6.355 cm moderator
   23   408  -2.635 -19  u=8 $detector
   24   256  -0.9300 -26 19  u=8 $moderator
   25     6 -0.001205 26  u=8 $air above moderator
c 6.99 cm moderator
   26   408  -2.635 -19  u=9 $detector
   27   256  -0.9300 -27 19  u=9 $moderator
   28     6 -0.001205 27  u=9 $air above moderator
c 7.625 cm moderator
   29   408  -2.635 -19  u=10 $detector
   30   256  -0.9300 -28 19  u=10 $moderator
   31     6 -0.001205 28  u=10 $air above moderator
c 8.26 cm moderator
   32   408  -2.635 -19  u=11 $detector
   33   256  -0.9300 -29 19  u=11 $moderator
   34     6 -0.001205 29  u=11 $air above moderator
c 8.895 cm moderator
   35   408  -2.635 -19  u=12 $detector
   36   256  -0.9300 -30 19  u=12 $moderator
   37     6 -0.001205 30  u=12 $air above moderator
c 9.53 cm moderator
   38   408  -2.635 -19  u=13 $detector
   39   256  -0.9300 -31 19  u=13 $moderator
   40     6 -0.001205 31  u=13 $air above moderator
c 10.165 cm moderator
   41   408  -2.635 -19  u=14 $detector
   42   256  -0.9300 -32 19  u=14 $moderator
   43     6 -0.001205 32  u=14 $air above moderator
c 10.8 cm moderator
   44   408  -2.635 -19  u=15 $detector
   45   256  -0.9300 -33 19  u=15 $moderator
   46     6 -0.001205 33  u=15 $air above moderator
c 11.435 cm moderator
```

```
   47   408  -2.635 -19  u=16 $detector
   48   256  -0.9300 -34 19  u=16 $moderator
   49     6 -0.001205 34  u=16 $air above moderator
c 12.07 cm moderator
   50   408  -2.635 -19  u=17 $detector
   51   256  -0.9300 -35 19  u=17 $moderator
   52     6 -0.001205 35  u=17 $air above moderator
c 12.705 cm moderator
   53   408  -2.635 -19  u=18 $detector
   54   256  -0.9300 -36 19  u=18 $moderator
   55     6 -0.001205 36  u=18 $air above moderator
c 13.34 cm moderator
   56   408  -2.635 -19  u=19 $detector
   57   256  -0.9300 -37 19  u=19 $moderator
   58     6 -0.001205 37  u=19 $air above moderator
c 13.975 cm moderator
   59   408  -2.635 -19  u=20 $detector
   60   256  -0.9300 -38 19  u=20 $moderator
   61     6 -0.001205 38  u=20 $air above moderator
c 14.61 cm moderator
   62   408  -2.635 -19  u=21 $detector
   63   256  -0.9300 -39 19  u=21 $moderator
   64     6 -0.001205 39  u=21 $air above moderator
c 15.245 cm moderator
   65   408  -2.635 -19  u=22 $detector
   66   256  -0.9300 -40 19  u=22 $moderator
   67     6 -0.001205 40  u=22 $air above moderator
c 22.865 cm moderator
   68   408  -2.635 -19  u=23 $detector
   69   256  -0.9300 -41 19  u=23 $moderator
   70     6 -0.001205 41  u=23 $air above moderator
c 0 cm moderator
   71   408  -2.635 -19  u=24 $detector
   72     6 -0.001205 19  u=24 $air above detector
c 1 in poly
   73   256  -0.9300 -42

c surfaces
c 1-6 Box defining void region
    1        pz 1030
    2        pz -28
    3        px 100
    4        px -100
```

```
    5        py 100
    6        py -100
c 7-12 Lattice Box
    7        pz 25
    8        pz -25
    9        px 50
   10        px -50
   11        py 10
   12        py -10
c   13        pz 25
c   14        pz -25
c 15-18 Lattice Cells
   15        px 2
   16        px -2
   17        py 2
   18        py -2
   19       rcc 0 0 -25 0 0 1 1  $detector
c 20-41 Moderators
   20       rpp -2 2 -2 2 -25 -22.455
   21       rpp -2 2 -2 2 -25 -21.82
   22       rpp -2 2 -2 2 -25 -21.185
   23       rpp -2 2 -2 2 -25 -20.55
   24       rpp -2 2 -2 2 -25 -19.915
   25       rpp -2 2 -2 2 -25 -19.28
   26       rpp -2 2 -2 2 -25 -18.645
   27       rpp -2 2 -2 2 -25 -18.01
   28       rpp -2 2 -2 2 -25 -17.375
   29       rpp -2 2 -2 2 -25 -16.74
   30       rpp -2 2 -2 2 -25 -16.105
   31       rpp -2 2 -2 2 -25 -15.47
   32       rpp -2 2 -2 2 -25 -14.835
   33       rpp -2 2 -2 2 -25 -14.2
   34       rpp -2 2 -2 2 -25 -13.565
   35       rpp -2 2 -2 2 -25 -12.93
   36       rpp -2 2 -2 2 -25 -12.295
   37       rpp -2 2 -2 2 -25 -11.66
   38       rpp -2 2 -2 2 -25 -11.025
   39       rpp -2 2 -2 2 -25 -10.39
   40       rpp -2 2 -2 2 -25 -9.755
   41       rpp -2 2 -2 2 -25 -2.135
   42       rpp -50 50 -10 10 -27.54 -25

mode n
```

```
c ---------------
c Materials
c ---------------
c     -- Mat  408 Lithium Fluoride --
c         density: 2.635E+00 g/cc
m408  3006.80c    -0.267585
      9019.80c    -0.732415
c     -- Mat  256  Polyethylene --
c         density: 9.300E-01 g/cc
m256  1001.80c    -0.143711
      6000.80c    -0.856289
c     -- Mat   6  Air-Dry --
c         density: 1.205E-03 g/cc
m6    6000.80c    -1.24e-04     7014.80c    -7.55268e-01
      8016.80c    -2.31781e-01  18036.80c   -1.2827e-02
imp:n  0            1 71r         $ 1, 73
c -----------------------------------------------------
c Source Description
c -----------------------------------------------------
sdef pos=0 0 0 x=d1 y=d2 z=1025 par=1 erg=1 vec=0 0 -1 dir=1
si1 -50 50 $ sampling range Xmin to Xmax
sp1  0  1  $ weighting for x sampling
si2 -10 10 $ sampling range Ymin to Ymax
sp2  0  1  $ weighting for y sampling
c sp3 -3
c
c      --------------------------------
c      Tally definitions
c      --------------------------------
fc24 Triton Production Rate in detector cells
f24:n (71<4[-12:-8 -2:2 0:0]<2) $p24
     (5<4[-12:-8 -2:2 0:0]<2)   $p24
     (8<4[-12:-8 -2:2 0:0]<2)   $p24
     (5<4[-7:-3 -2:2 0:0]<2)    $p2
     (8<4[-7:-3 -2:2 0:0]<2)    $p2
     (11<4[-7:-3 -2:2 0:0]<2)   $p2
     (20<4[-2:2 -2:2 0:0]<2)    $p7
     (23<4[-2:2 -2:2 0:0]<2)    $p7
     (26<4[-2:2 -2:2 0:0]<2)    $p7
     (38<4[3:7 -2:2 0:0]<2)     $p13
     (41<4[3:7 -2:2 0:0]<2)     $p13
     (44<4[3:7 -2:2 0:0]<2)     $p13
     (44<4[8:12 -2:2 0:0]<2)    $p15
```

```
     (47<4[8:12 -2:2 0:0]<2)    $p15
     (50<4[8:12 -2:2 0:0]<2)    $p15
fm24 -1 408 105
nps 1e8
print
prdmp 0 0 1 0 0
```

5x30 Detector Array MCNP Input Code

```
Pyramid Li-6 Detector Array 5x30
c cells
    1     0           1 :-2 :3 :-4 :5 :-6  $void
    2     6 -0.001205 -7 8 -9 10 -11 12  fill=1 $detector region
    3     6 -0.001205 #1 #2  $source region
    4     6 -0.001205 -15 16 -17 18  u=1 lat=1 $ROW 1 lattice definition
            fill=-15:14 -2:2 0:0
      24  24  24  24  24   2   2   2   2   2   7   7   7   7   7  13  13  13
             13  13  15  15  15  15  15  25 25 25 25 25 $ROW 1
      24   2   2   2  24   2   3   3   3   2   7   8   8   8   7  13  14  14
             14  13  15  16  16  16  15 25 25 25 25 25 $ROW 2
      24   2   3   2  24   2   3   4   3   2   7   8   9   8   7  13  14  15
             14  13  15  16  17  16  15 25 25 25 25 25 $ROW 3
      24   2   2   2  24   2   3   3   3   2   7   8   8   8   7  13  14  14
             14  13  15  16  16  16  15 25 25 25 25 25 $ROW 4
      24  24  24  24  24   2   2   2   2   2   7   7   7   7   7  13  13  13
             13  13  15  15  15  15  15 25 25 25 25 25 $ROW 5
c ----------------------------------------------------
c Universe Key
c    Universe 1- Lattice Box
c    Universe 2- 2.545   cm moderator
c    Universe 3- 3.18    cm moderator
c    Universe 4- 3.815   cm moderator
c    Universe 5- 4.45    cm moderator
c    Universe 6- 5.085   cm moderator
c    Universe 7- 5.72    cm moderator
c    Universe 8- 6.355   cm moderator
c    Universe 9- 6.99    cm moderator
c    Universe 10- 7.625  cm moderator
c    Universe 11- 8.26   cm moderator
c    Universe 12- 8.895  cm moderator
c    Universe 13- 9.53   cm moderator
c    Universe 14- 10.165 cm moderator
c    Universe 15- 10.8   cm moderator
c    Universe 16- 11.435 cm moderator
```

```
c    Universe 17- 12.07  cm moderator
c    Universe 18- 12.705 cm moderator
c    Universe 19- 13.34  cm moderator
c    Universe 20- 13.975 cm moderator
c    Universe 21- 14.61  cm moderator
c    Universe 22- 15.245 cm moderator
c    Universe 23- 22.865 cm moderator
c    Universe 24- 0      cm moderator
c    Universe 25- 7.625  cm moderator with 2.54 cm Be layer
c ----------------------------------------------------
c Moderators
c 2.545 cm moderator
    5   408  -2.635 -19  u=2 $detector
    6   256  -0.9300 -20 19  u=2 $moderator
    7     6 -0.001205 20  u=2 $air above moderator
c 3.18 cm moderator
    8   408  -2.635 -19  u=3 $detector
    9   256  -0.9300 -21 19  u=3 $moderator
   10     6 -0.001205 21  u=3 $air above moderator
c 3.815 cm moderator
   11   408  -2.635 -19  u=4 $detector
   12   256  -0.9300 -22 19  u=4 $moderator
   13     6 -0.001205 22  u=4 $air above moderator
c 4.45 cm moderator
   14   408  -2.635 -19  u=5 $detector
   15   256  -0.9300 -23 19  u=5 $moderator
   16     6 -0.001205 23  u=5 $air above moderator
c 5.085 cm moderator
   17   408  -2.635 -19  u=6 $detector
   18   256  -0.9300 -24 19  u=6 $moderator
   19     6 -0.001205 24  u=6 $air above moderator
c 5.72 cm moderator
   20   408  -2.635 -19  u=7 $detector
   21   256  -0.9300 -25 19  u=7 $moderator
   22     6 -0.001205 25  u=7 $air above moderator
c 6.355 cm moderator
   23   408  -2.635 -19  u=8 $detector
   24   256  -0.9300 -26 19  u=8 $moderator
   25     6 -0.001205 26  u=8 $air above moderator
c 6.99 cm moderator
   26   408  -2.635 -19  u=9 $detector
   27   256  -0.9300 -27 19  u=9 $moderator
   28     6 -0.001205 27  u=9 $air above moderator
```

```
c 7.625 cm moderator
   29   408  -2.635 -19  u=10 $detector
   30   256  -0.9300 -28 19  u=10 $moderator
   31     6 -0.001205 28  u=10 $air above moderator
c 8.26 cm moderator
   32   408  -2.635 -19  u=11 $detector
   33   256  -0.9300 -29 19  u=11 $moderator
   34     6 -0.001205 29  u=11 $air above moderator
c 8.895 cm moderator
   35   408  -2.635 -19  u=12 $detector
   36   256  -0.9300 -30 19  u=12 $moderator
   37     6 -0.001205 30  u=12 $air above moderator
c 9.53 cm moderator
   38   408  -2.635 -19  u=13 $detector
   39   256  -0.9300 -31 19  u=13 $moderator
   40     6 -0.001205 31  u=13 $air above moderator
c 10.165 cm moderator
   41   408  -2.635 -19  u=14 $detector
   42   256  -0.9300 -32 19  u=14 $moderator
   43     6 -0.001205 32  u=14 $air above moderator
c 10.8 cm moderator
   44   408  -2.635 -19  u=15 $detector
   45   256  -0.9300 -33 19  u=15 $moderator
   46     6 -0.001205 33  u=15 $air above moderator
c 11.435 cm moderator
   47   408  -2.635 -19  u=16 $detector
   48   256  -0.9300 -34 19  u=16 $moderator
   49     6 -0.001205 34  u=16 $air above moderator
c 12.07 cm moderator
   50   408  -2.635 -19  u=17 $detector
   51   256  -0.9300 -35 19  u=17 $moderator
   52     6 -0.001205 35  u=17 $air above moderator
c 12.705 cm moderator
   53   408  -2.635 -19  u=18 $detector
   54   256  -0.9300 -36 19  u=18 $moderator
   55     6 -0.001205 36  u=18 $air above moderator
c 13.34 cm moderator
   56   408  -2.635 -19  u=19 $detector
   57   256  -0.9300 -37 19  u=19 $moderator
   58     6 -0.001205 37  u=19 $air above moderator
c 13.975 cm moderator
   59   408  -2.635 -19  u=20 $detector
   60   256  -0.9300 -38 19  u=20 $moderator
```

```
   61     6 -0.001205 38  u=20 $air above moderator
c 14.61 cm moderator
   62   408  -2.635 -19  u=21 $detector
   63   256  -0.9300 -39 19  u=21 $moderator
   64     6 -0.001205 39  u=21 $air above moderator
c 15.245 cm moderator
   65   408  -2.635 -19  u=22 $detector
   66   256  -0.9300 -40 19  u=22 $moderator
   67     6 -0.001205 40  u=22 $air above moderator
c 22.865 cm moderator
   68   408  -2.635 -19  u=23 $detector
   69   256  -0.9300 -41 19  u=23 $moderator
   70     6 -0.001205 41  u=23 $air above moderator
c 0 cm moderator
   71   408  -2.635 -19  u=24 $detector
   72     6 -0.001205 19  u=24 $air above detector
c 7.625 cm moderator with 2.54 cm Be layer
   73   408  -2.635 -19  u=25 $detector
   74   256   -0.93 -28 19  u=25 $moderator
   75     6 -0.001205 -42  u=25 $air above Be
   76     4  -1.848 #73 #74 #75  u=25 $Be layer

c surfaces
c 1-6 Box defining void region
    1        pz 1030
    2        pz -26
    3        px 100
    4        px -100
    5        py 100
    6        py -100
c 7-12 Lattice Box
    7        pz 25
    8        pz -25
    9        px 60
   10        px -60
   11        py 10
   12        py -10
c 15-18 Lattice Cells
   15        px 4
   16        px 0
   17        py 2
   18        py -2
   19       rcc 2 0 -25 0 0 1 1  $detector
```

```
c 20-41 Moderators
   20       rpp 0 4 -2 2 -25 -22.455
   21       rpp 0 4 -2 2 -25 -21.82
   22       rpp 0 4 -2 2 -25 -21.185
   23       rpp 0 4 -2 2 -25 -20.55
   24       rpp 0 4 -2 2 -25 -19.915
   25       rpp 0 4 -2 2 -25 -19.28
   26       rpp 0 4 -2 2 -25 -18.645
   27       rpp 0 4 -2 2 -25 -18.01
   28       rpp 0 4 -2 2 -25 -17.375
   29       rpp 0 4 -2 2 -25 -16.74
   30       rpp 0 4 -2 2 -25 -16.105
   31       rpp 0 4 -2 2 -25 -15.47
   32       rpp 0 4 -2 2 -25 -14.835
   33       rpp 0 4 -2 2 -25 -14.2
   34       rpp 0 4 -2 2 -25 -13.565
   35       rpp 0 4 -2 2 -25 -12.93
   36       rpp 0 4 -2 2 -25 -12.295
   37       rpp 0 4 -2 2 -25 -11.66
   38       rpp 0 4 -2 2 -25 -11.025
   39       rpp 0 4 -2 2 -25 -10.39
   40       rpp 0 4 -2 2 -25 -9.755
   41       rpp 0 4 -2 2 -25 -2.135
   42       rpp 0 4 -2 2 -14.835 25 $air above Be layer

mode n
c ---------------
c Materials
c ---------------
c     -- Mat  408 Lithium Fluoride --
c         density: 2.635E+00 g/cc
m408  3006.80c    -0.267585
      9019.80c    -0.732415
c     -- Mat  256  Polyethylene --
c         density: 9.300E-01 g/cc
m256  1001.80c    -0.143711
      6000.80c    -0.856289
c     -- Mat   6  Air-Dry --
c         density: 1.205E-03 g/cc
m6    6000.80c    -1.24e-04     7014.80c    -7.55268e-01
      8016.80c    -2.31781e-01  18036.80c   -1.2827e-02
c     -- Mat  4  Beryllium --
c         density: 1.848E+00 g/cc
```

```
m4    4007.80c     1
imp:n  0            1 74r         $ 1, 76
c -------------------------------------------------------
c Source Description
c -------------------------------------------------------
sdef pos=0 0 0 x=d1 y=d2 z=1025 par=1 erg=5 vec=0 0 -1 dir=1
si1 -60 60 $ sampling range Xmin to Xmax
sp1  0  1  $ weighting for x sampling
si2 -10 10 $ sampling range Ymin to Ymax
sp2  0  1  $ weighting for y sampling
c sp3 -3
c
c      --------------------------------
c      Tally definitions
c      --------------------------------
fc24 Triton Production Rate in detector cells
f24:n (71<4[-15:-11 -2:2 0:0]<2) $p24
     (5<4[-15:-11 -2:2 0:0]<2)   $p24
     (8<4[-15:-11 -2:2 0:0]<2)   $p24
     (5<4[-10:-6 -2:2 0:0]<2)    $p2
     (8<4[-10:-6 -2:2 0:0]<2)    $p2
     (11<4[-10:-6 -2:2 0:0]<2)   $p2
     (20<4[-5:1 -2:2 0:0]<2)    $p7
     (23<4[-5:1 -2:2 0:0]<2)    $p7
     (26<4[-5:1 -2:2 0:0]<2)    $p7
     (38<4[0:4 -2:2 0:0]<2)     $p13
     (41<4[0:4 -2:2 0:0]<2)     $p13
     (44<4[0:4 -2:2 0:0]<2)     $p13
     (44<4[5:9 -2:2 0:0]<2)    $p15
     (47<4[5:9 -2:2 0:0]<2)    $p15
     (50<4[5:9 -2:2 0:0]<2)    $p15
     (73<4[10:14 -2:2 0:0]<2)    $3" moderator block with Be layer
fm24 -1 408 105
nps 1e8
print
prdmp 0 0 1 0 0
```

APPENDIX G

FISSION SOURCE DISTRIBUTIONS

Table 29. ^{241}AmBe Source

^{241}AmBe			
E(MeV)		E(MeV)	
4.14E-07	0.00000000000000E+00	5.68E+00	2.33193494891863E-02
1.10E-01	1.43636436924211E-02	5.89E+00	2.05848017155568E-02
3.30E-01	3.33978135755105E-02	6.11E+00	1.81520338824044E-02
5.40E-01	3.12722568037099E-02	6.32E+00	1.76734434920621E-02
7.50E-01	2.81199481328063E-02	6.54E+00	2.03939025569633E-02
9.70E-01	2.50020624747994E-02	6.75E+00	1.82994915214768E-02
1.18E+00	2.13611274098887E-02	6.96E+00	1.62988677537254E-02
1.40E+00	1.98311045846622E-02	7.18E+00	1.67736307967407E-02
1.61E+00	1.74702427968949E-02	7.39E+00	1.68069291576870E-02
1.82E+00	1.92485645684962E-02	7.61E+00	1.88333504984568E-02
2.04E+00	2.22520948196471E-02	7.82E+00	1.83744333114470E-02
2.25E+00	2.14577094308846E-02	8.03E+00	1.68804830567239E-02
2.47E+00	2.24823921960773E-02	8.25E+00	1.43522250379851E-02
2.68E+00	2.27660216433234E-02	8.46E+00	9.67734970954390E-03
2.90E+00	2.95063344836539E-02	8.68E+00	6.52077818374818E-03
3.11E+00	3.55852025021457E-02	8.89E+00	4.25518271193271E-03
3.32E+00	3.68529199998114E-02	9.11E+00	3.66684926190803E-03
3.54E+00	3.45832879331172E-02	9.32E+00	3.80591621008074E-03
3.75E+00	3.06586880290906E-02	9.53E+00	5.05803419587466E-03
3.97E+00	2.99873939810261E-02	9.75E+00	6.25338345215875E-03
4.18E+00	2.69065692592094E-02	9.96E+00	5.51923472596848E-03
4.39E+00	2.86265006414423E-02	1.02E+01	4.67545905853612E-03
4.61E+00	3.17841094489603E-02	1.04E+01	3.69580171196546E-03
4.82E+00	3.07367890272267E-02	1.06E+01	2.78141724495708E-03
5.04E+00	3.33402190535138E-02	1.08E+01	1.51396546853315E-03
5.25E+00	3.04123859175902E-02	1.10E+01	3.63306381109726E-04
5.47E+00	2.73807100668483E-02	1.11E+01	0.00000000000000E+00

Table 30. ^{241}AmB Source

^{241}AmB			
E(MeV)		E(MeV)	
4.14E-07	0.00000000000000E+00	4.13E+00	1.97926394069784E-02
8.20E-01	1.75437281985207E-02	4.27E+00	1.72349292783449E-02
1.09E+00	1.12997568081062E-02	4.41E+00	1.44851271359815E-02
1.34E+00	8.07383398292112E-03	4.55E+00	9.96956137780932E-03
1.56E+00	2.09782366072103E-02	4.69E+00	7.45511597585092E-03
1.78E+00	4.53830748066365E-02	4.83E+00	3.41201068393002E-03
1.98E+00	6.31447038786529E-02	4.96E+00	2.19379595577650E-03
2.17E+00	7.99016415216460E-02	5.09E+00	1.16165683316923E-03
2.36E+00	8.89705185742596E-02	5.22E+00	3.02634855985391E-04
2.54E+00	9.26131021110874E-02	5.35E+00	2.68130833245710E-04
2.72E+00	9.65395969812196E-02	5.48E+00	2.36003948711250E-04
2.89E+00	8.30557318885157E-02	5.61E+00	1.15352443387429E-04
3.05E+00	7.05894659284232E-02	5.74E+00	1.45239831652156E-04
3.22E+00	6.67149157925059E-02	5.86E+00	1.39453250555188E-04
3.38E+00	4.99491804367687E-02	5.98E+00	2.77712211918583E-04
3.53E+00	4.02089215029575E-02	6.11E+00	1.78071379229578E-03
3.68E+00	3.17105395015533E-02	6.19E+00	2.91386222691218E-04
3.83E+00	3.03236067178917E-02	6.25E+00	0.00000000000000E+00
3.98E+00	2.52399795801911E-02		

Table 31. ^{252}Cf in D2O sphere with 150mm radius

^{252}Cf in D2O sphere with 150mm radius			
E(MeV)		E(MeV)	
4.14E-07	0.00000000000000E+00	7.00E-01	7.83085453522472E-03
1.00E-06	1.89606200608717E-02	8.00E-01	6.78339474532575E-03
1.00E-05	6.30908315480368E-02	9.00E-01	5.74781214003151E-03
5.00E-05	6.03539217162788E-02	1.00E+00	3.57172148080031E-03
1.00E-04	3.16768261515895E-02	1.20E+00	7.47518382855214E-03
2.00E-04	3.41028412835492E-02	1.40E+00	8.43204218655103E-03
4.00E-04	3.81924096488530E-02	1.60E+00	9.13354725551736E-03
7.00E-04	3.27934851730158E-02	1.80E+00	8.55104838865344E-03
1.00E-03	2.24348539737463E-02	2.00E+00	8.07061549938949E-03
3.00E-03	7.55845254603659E-02	2.30E+00	1.33752178853027E-02
6.00E-03	5.08770030531000E-02	2.60E+00	1.44670740068952E-02
1.00E-02	3.79032612834366E-02	3.00E+00	1.48824877386300E-02
2.00E-02	5.46893125461797E-02	3.50E+00	1.23474694541634E-02

4.00E-02	5.11542619253240E-02	4.00E+00	8.18547436788323E-03
6.00E-02	2.95989528918960E-02	4.50E+00	8.10347285315919E-03
8.00E-02	1.99939040353988E-02	5.00E+00	6.54288802235100E-03
1.00E-01	1.45489595456865E-02	6.00E+00	8.69673825907164E-03
1.50E-01	2.47333715945980E-02	7.00E+00	4.93282175447226E-03
2.00E-01	1.59375868138287E-02	8.00E+00	2.41691820650386E-03
2.50E-01	1.14249498272875E-02	9.00E+00	1.29561339222022E-03
3.00E-01	8.89729197154498E-03	1.00E+01	7.65970948832398E-04
3.50E-01	6.56681896064120E-03	1.10E+01	4.43192336090110E-04
4.00E-01	4.88724897005754E-03	1.20E+01	1.61841161200711E-04
4.50E-01	2.65011830226863E-03	1.30E+01	1.24066196893981E-04
5.00E-01	3.13974336660322E-03	1.40E+01	5.92863777229773E-05
5.50E-01	4.20317892937073E-03	1.50E+01	2.82870773096502E-05
6.00E-01	4.11563813160948E-03		

Table 32. ^{252}Cf in polyethylene sphere with 12 in diameter

^{252}Cf in polyethylene sphere with 12 in diameter			
E(MeV)		E(MeV)	
1.00E-10	0	3.98E-02	1.57E-08
1.00E-09	4.12E-10	5.01E-02	1.61E-08
2.15E-09	1.56E-09	6.30E-02	1.73E-08
4.64E-09	6.84E-09	7.94E-02	1.95E-08
1.00E-08	3.07E-08	1.00E-01	2.07E-08
2.15E-08	1.20E-07	1.25E-01	2.29E-08
4.64E-08	3.30E-07	1.58E-01	2.66E-08
1.00E-07	4.66E-07	1.99E-01	3.06E-08
2.15E-07	2.03E-07	2.51E-01	3.46E-08
4.64E-07	4.87E-08	3.16E-01	4.09E-08
1.00E-06	4.16E-08	3.98E-01	4.80E-08
2.15E-06	3.94E-08	5.01E-01	5.53E-08
4.64E-06	3.87E-08	6.30E-01	6.66E-08
1.00E-05	3.71E-08	7.94E-01	7.76E-08
2.15E-05	3.65E-08	1.00E+00	9.02E-08
4.64E-05	3.76E-08	1.25E+00	9.97E-08
1.00E-04	3.67E-08	1.58E+00	1.21E-07
2.15E-04	3.68E-08	1.99E+00	1.30E-07
4.64E-04	3.65E-08	2.51E+00	1.37E-07
1.00E-03	3.74E-08	3.16E+00	1.28E-07
2.15E-03	3.73E-08	3.98E+00	1.07E-07

4.64E-03	3.85E-08	5.01E+00	1.04E-07
1.00E-02	4.14E-08	6.30E+00	7.51E-08
1.25E-02	1.21E-08	7.94E+00	4.46E-08
1.58E-02	1.30E-08	1.00E+01	1.91E-08
1.99E-02	1.34E-08	1.15E+01	4.95E-09
2.51E-02	1.45E-08	2.50E+01	3.06E-09
3.16E-02	1.47E-08		

Table 33. ^{252}Cf in iron sphere with a 60 cm diameter

^{252}Cf in iron sphere with a 60 cm diameter			
E(MeV)		E(MeV)	
1.00E-11	0	6.00E-01	3.68151E-07
4.14E-07	7.41311E-11	7.00E-01	8.33922E-07
1.00E-06	1.79690E-10	8.00E-01	2.32676E-07
1.00E-05	2.16423E-09	9.00E-01	2.08674E-07
5.00E-05	3.42060E-09	1.00E+00	2.07162E-07
1.00E-04	1.92405E-09	1.20E+00	2.45645E-07
2.00E-04	2.44965E-09	1.40E+00	1.14349E-07
4.00E-04	2.65359E-09	1.60E+00	5.90811E-08
7.00E-04	2.47477E-09	1.80E+00	4.98952E-08
1.00E-03	2.01513E-09	2.00E+00	2.86194E-08
3.00E-03	1.13243E-08	2.30E+00	2.94511E-08
6.00E-03	1.20095E-08	2.60E+00	1.48005E-08
1.00E-02	4.29549E-09	3.00E+00	1.32787E-08
2.00E-02	5.23423E-08	3.50E+00	7.85963E-09
3.00E-02	4.40399E-07	4.00E+00	5.21796E-09
4.00E-02	2.16687E-08	4.50E+00	3.20459E-09
6.00E-02	8.95549E-08	5.00E+00	2.18598E-09
8.00E-01	1.81436E-07	6.00E+00	2.35471E-09
1.00E-01	1.41091E-07	7.00E+00	1.37509E-09
1.50E-01	6.16652E-07	8.00E+00	8.17777E-10
2.00E-01	5.68099E-07	9.00E+00	5.51874E-10
2.50E-01	3.80320E-07	1.00E+01	4.01716E-10
3.00E-01	6.75844E-07	1.10E+01	1.42645E-10
3.50E-01	8.98504E-07	1.20E+01	1.23212E-10
4.00E-01	4.84431E-07	1.30E+01	6.20675E-11
4.50E-01	1.59911E-07	1.40E+01	9.98291E-12
5.00E-01	2.98644E-07	1.50E+01	1.76761E-11
5.50E-01	2.19679E-07		

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